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April 22, 1942.

CORROSION IN SOILS

Abstract

This paper is a summary and restatement of observations related to underground corrosion that have been presented in publications of the National Bureau of Standards and in technical books and journals dealing with corrosion. Its purpose is to answer questions frequently sent in to the Bureau regarding corrosion.

Underground corrosion is the result of a wide variety of forces, and an accurate prediction of the performance of an individual piece of metal is not to be expected. However, the average performance of an adequate number of specimens of a metal under specified conditions can be predicted roughly.

Differences of potential which are the chief causes of underground corrosion may originate in differences in the metal or soil, or in conditions incidental to the manner in which a pipe line or other metal structure is installed. Some of the causes of corrosion can be readily recognized and avoided; others may not be easily recognized, or may be unavoidable though known.

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I. INTRODUCTION.

The purpose of this paper is to answer frequently recurring questions as to the corrosivity of soils, the identification of corrosive conditions, and the prevention or reduction of corrosion losses. The paper is intended for the information of the non-technical inquirer who has a specific corrosion problem for which he desires a practical solution. In order to understand the suggestions that are offered the reader must have a certain amount of information about soils and corrosion phenomena. For this reason some of the characteristics of soils, metals and coatings are discussed. For those who care to go more deeply into the subject, references to some of the more important books and articles dealing with corrosion are given. To enable those generally familiar with soils and corrosion to find the discussion of the topic with which they are concerned without profitless reading, the discussion of the characteristics of soils and corrosion has been separated from the discussion of their effects. This has necessitated some repetition.

The paper is chiefly a résumé of material already published and contains no new data. In certain cases suggestions have been made regarding the mitigation of corrosion which are based on the judgment of the author rather than on the direct results of specific tests or experiments. These passages have been identified.

II. THEORY OF CORROSION AS RELATED TO BURIED METALS.

Most corrosion can be accounted for by the electrochemical theory, which postulates a difference of potential between two points on a metallic conductor exposed to an electrolyte. Positively charged metal atoms, ions, are removed from that part of the surface undergoing corrosion, the anode, and reactions between these ions and others from the electrolyte result in a flow of current and the deposition of hydrogen or other material at the non-corroding surface (cathode). Material may also be deposited at or near the corroding surface. Often these reactions control the rate of corrosion by their effects on the potentials of the metal surfaces or on the resistance of the electrical circuit.

The difference of potential which may be regarded as the cause of corrosion is analogous to a difference in temperature or a difference in the pressure between two points in a fluid. It represents the tendency of the metal to go into solution, but it does not indicate the rate of corrosion. The rate of corrosion is more closely related to the amount of current leaving the anode, but the measurement of this current is usually difficult if not impossible except under special conditions in the laboratory.

The effect of the flow of current on the potentials of the electrodes in soils under certain controlled conditions has been discussed by Denison (1)¹. The changes studied by

¹Figures in parentheses indicate the literature references at the end of this paper.

Denison occur quickly and largely disappear if for any reason the current is interrupted for a short time. More permanent changes in current result from deposition of solid deposits of primary or secondary corrosion products.

The resultant of all of these changes on the progress of pitting is illustrated in figure 1, which is taken from a report (2) on soil-corrosion work at the National Bureau of Standards. The rapid changes in the rates of corrosion indicated by the curvatures of the lines near their origin

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is attributable in part to changing conditions in the backfill of the trench in which the pipe was buried. After three or four years the trench and electrical conditions become stable, and the increase in corrosion is roughly proportional to the change in the duration of the exposure. In some soils, chiefly those which are well aerated, this increase is very small and pipes having a wall thickness of 0.10 inch or more may last a very long time. In soils which are poorly aerated, high in acidity or in soluble salts, the rate of corrosion of iron is maintained and under some conditions the rate appears to increase with the period of exposure (3).

The decrease in the rate of corrosion of iron in soils over long periods of time has been discussed from a theoretical standpoint by Fetherstonhaugh (4), by Brennan (5) and by Hoff (6), and the relation between pit depths or loss of weight and time has been expressed by empirical equations by Scott (7) and Putnam (8).

Originally, impurities, inclusions and strains in the metal were regarded as the chief causes of the differences of potential, and a very pure commercial iron was developed as a corrosion-resistant material. Mill scale was also thought to be an important cause of corrosion, and one rolling mill developed a "scale free" pipe on this account. Somewhat later the theory of protective films resulting from initial corrosion was promulgated and efforts were made to formulate alloy steels that would produce protective layers or films of oxides or other corrosion products. The success of some of these efforts will be discussed later. Exposure tests of ferrous pipe materials called attention to the wide range of the rates of corrosion of the same material in different soils and the similarity of the rates of corrosion of different ferrous materials in the same soil. As a result of these observations, attention was turned to soils as an important factor in the rates of corrosion of buried metals. Still later Evans' (9) theory of differential aeration offered a satisfactory explanation for the cause of much underground corrosion.

According to this theory, the surface of steel abundantly supplied with oxygen is cathodic with respect to parts of the same surface less accessible to oxygen. Since the rate at which oxygen can reach buried metal varies greatly with the texture of the soil, its moisture content, and the depth of burial of the metal, differential aeration is especially important with respect to underground corrosion. Shepard (10) produced in the laboratory a difference of potential of 0.9 volt between wet and dry soil from the same source placed on a sheet of steel.

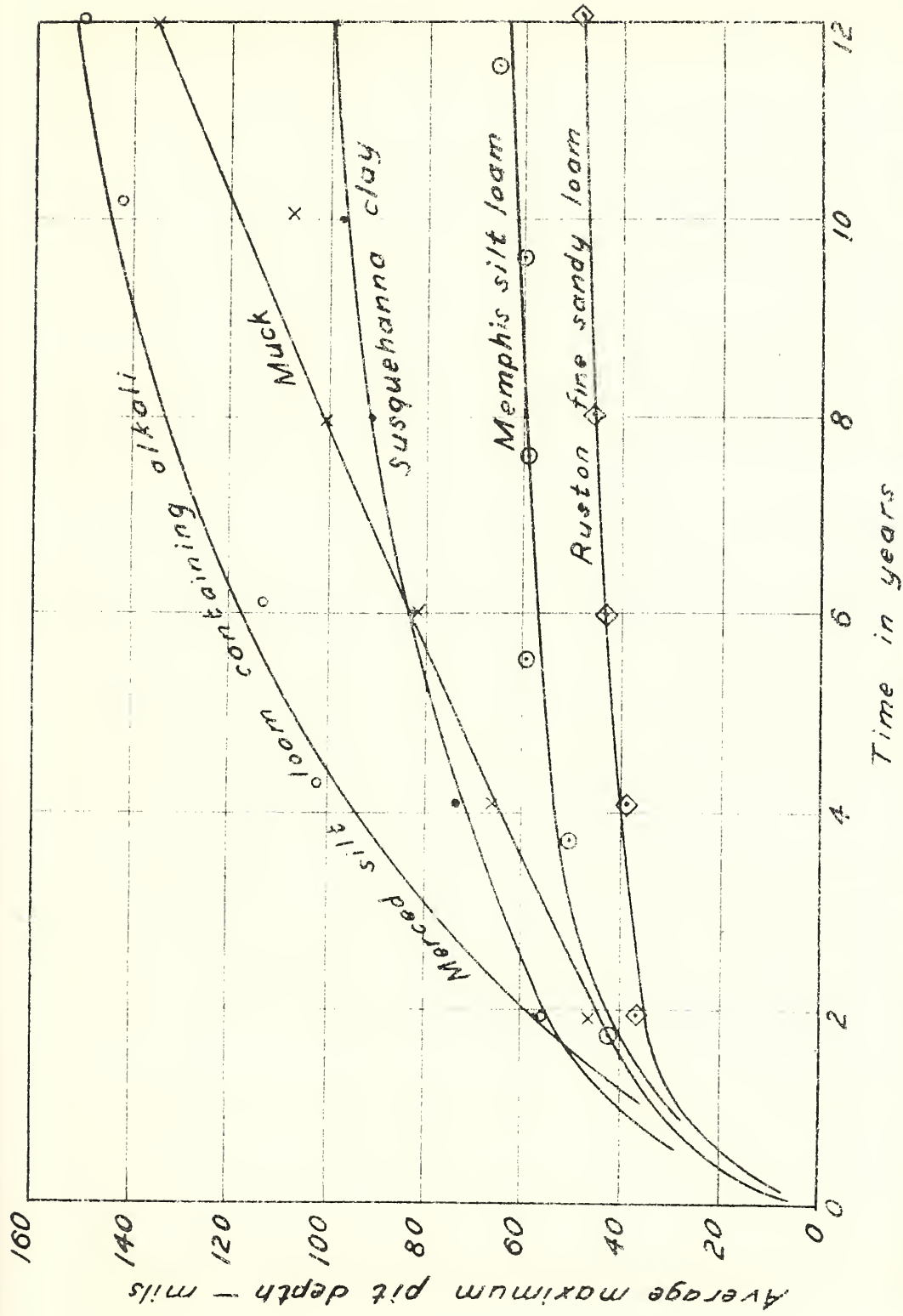


Figure 1 Change in rate of corrosion with time.

In 1934 an additional factor which under some conditions may influence the rate of corrosion was proposed by von Wolzogen Kühr and van der Vlugt (11) who showed that corrosion was accelerated in the presence of sulfate-reducing bacteria. The bacteria discussed by von Wolzogen Kühr are active only under anaerobic conditions. Beckwith (12) has suggested that some aerobic bacteria also may influence corrosion. The chemical changes associated with corrosion in the absence and presence of bacteria are summarized by Hadley (3).

The theory of corrosion is discussed at length by Evans (9), Burns (13), Speller (14) and Hoar (15) and to a less extent by the authors of many articles dealing with some phase of corrosion.

III. SOILS.

Pedology, the science of soils, was developed to promote agriculture. However, since soils constitute an environment of corroding metals and affect the rate of corrosion, a certain familiarity with pedology is helpful to those concerned with corrosion. In this section of the paper the discussion will be limited to the characteristics and properties of soils as such. The effects of soils on corrosion will be discussed in a subsequent section.

1. Definition and Classification.

A soil maybe defined as two or more layers of finely divided, modified rock material, having well defined characteristics. In general, the term soil is applied to the first few feet of material covering the level and moderately inclined portions of the earth. Crushed rock or unmodified rock on mountain tops is not soil and, strictly speaking, earth removed from its original position is not soil if it has lost its structure. Classification of soils is based on their physical and chemical characteristics and not on their geologic origin or geographic location, although the soil characteristics may be influenced by both the origin and the location of the soil.

Soils may be divided broadly into two classes— those in which lime accumulates in the subsoil (Pedocal) and those in which it does not (Pedalfers). In the United States the first class lies generally west of a north and south line from north-western Minnesota to a point on the Gulf of Mexico 100 miles north of the Mexican border. Marbut (16) has classified the well developed soils of the continental United States into eight great soil groups to which he has added several groups of undeveloped soils among which are muck, peat, rough stony land,

sand and some others. Figure 2 shows the location of the great soil groups. In table 1 are given brief descriptions of the typical profiles of the great soil groups according to the Soil Survey Division, U. S. Department of Agriculture (17). Following the usual practice among soil investigators, the surface layer or horizon is designated by the letter A, the subsoil by the letter B, and the partially weathered parent material by the letter C.

Each great group contains from nine to sixty subgroups known as soil series, each of which is further subdivided with respect to type, i.e., as to the texture of the uppermost layer of soil. The three layers or horizons comprising the profile of most soil types may differ widely in texture, color, and composition. A soil name consists of two parts; the first designates the series and the second the type. The series name is usually taken from the locality where it was first identified; the type name describes the texture of the uppermost layer or A horizon.

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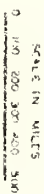


Figure 2 Soil groups of the United States.

Table 1.—Description of typical profiles in great soil groups.

Class	Soil groups	Description of profile	Reaction of profile	Soil name
I	Podzol	<p>Ao a few inches of leaf mat</p> <p>A1 very thin dark gray</p> <p>A2 whitish gray, a few inches thick</p> <p>B1 dark or coffee brown</p> <p>B2 yellowish-brown</p>	Strongly acid	Gloucester sandy loam Merrimac gravelly sandy loam
	Brown podzolic	<p>Ao leaf mat and acid humus</p> <p>A1 thin, dark gray</p> <p>A2 thin, gray brown or yellowish brown</p> <p>B brown, only slightly heavier than surface soil</p>	acid	
II	Gray-brown podzolic	<p>Ao thin leaf litter and mild humus</p> <p>A1 dark colored, 2 to 4 inches thick</p> <p>A2 grayish brown, leached horizon extending to 8-10 inches</p> <p>B yellowish brown to light reddish brown, definitely heavier in texture</p>	acid	Hagerstown loam Chester loam Sassafras silt loam Miami clay loam Miami silt loam Lindley silt loam Penn silt loam Mahoning silt loam
	Yellow podzolic	<p>Ao thin, dark colored organic covering</p> <p>A1 pale yellowish-gray leached layer 6 inches to 3 feet thick</p> <p>B heavy, yellow</p> <p>C red, and gray mottled parent material</p>	acid	Kalmia fine sandy loam Norfolk sandy loam Ruston sandy loam
III	Red podzolic	<p>Ao thin organic layer</p> <p>A1 yellowish-brown or grayish-brown leaching layer</p> <p>B deep-red</p> <p>C mottled, red, yellow, and gray</p>		Occil clay loam Memphis silt loam Susquehanna clay

Table 1 (Cont'd)

Class	Soil groups	Description of profile	Reaction of profile	Soil name
IV	Prairie	A very dark brown or grayish-brown B brown C light colored parent material at 2 to 5 feet	Slightly acid surface, soil neutral to alkaline subsoil	Marshall silt loam Summit silt loam
V	Chernozem	A black or very dark grayish-brown friable soil to a depth ranging from 3 to 4 feet B light-colored to whitish lime accumulation	alkaline	Fargo clay loam
VI	Dark brown soils	A dark-brown or dark grayish-brown B light-gray or white calcareous material at 1 1/2 to 2 feet	alkaline	
VII	Brown soils	A brown B light gray or white calcareous layer at 1 to 2 feet	alkaline	
VIII	Gray desert soils	A light grayish brown or gray low in organic matter B light in color, high in lime often high in soluble salts	alkaline	Mohave sandy loam Panoche clay loam
	Soils of Pacific Valleys	A brown, reddish brown or red, friable soil B heavy, tough, more intense in color	neutral to slightly alkaline	Ramona loam
	Rendzina (Immature soils developed from marl)	A dark-gray or black granular soil B soft, light gray calcareous material	alkaline	Houston black clay loam

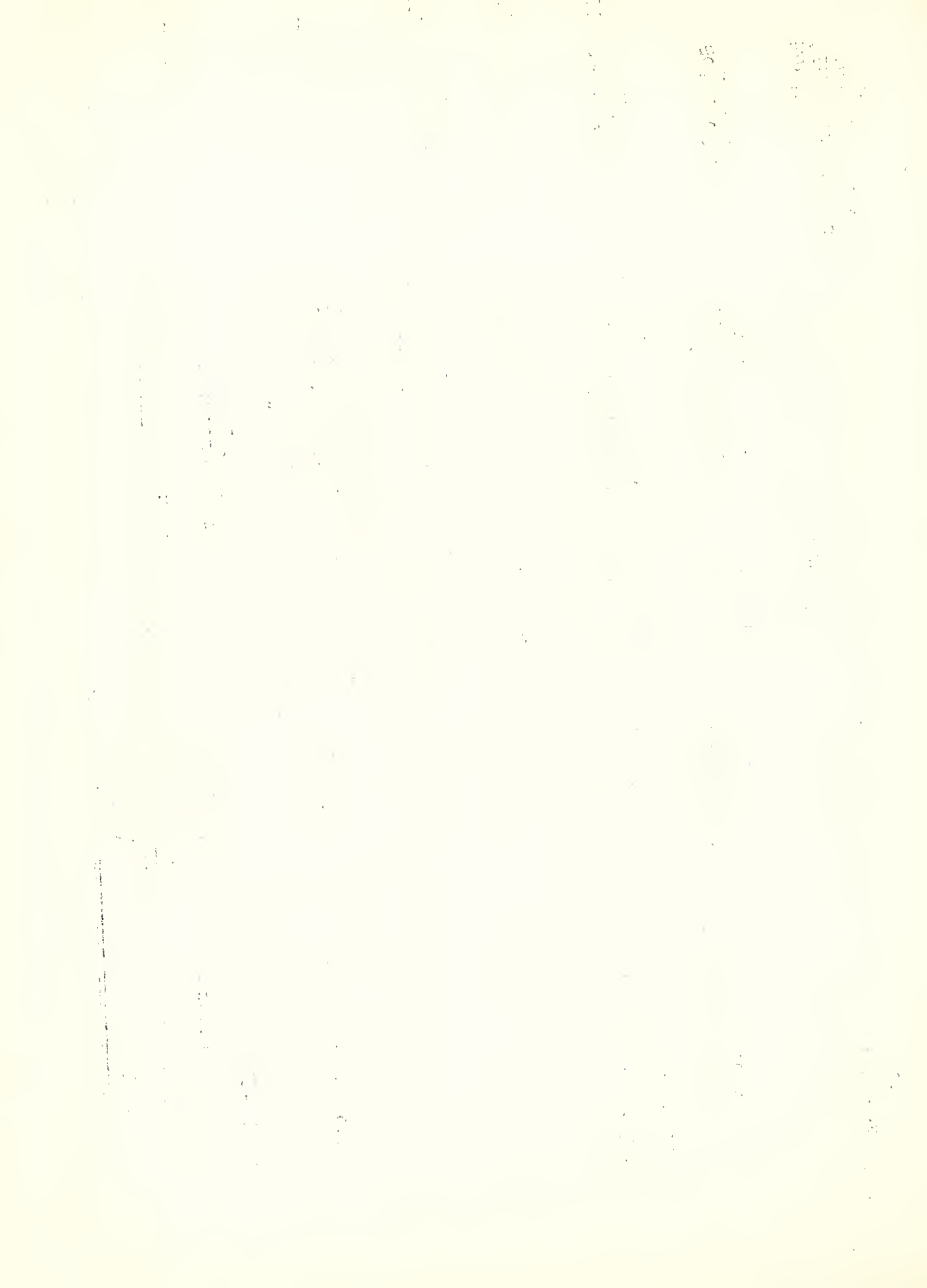


Table 1 (Cont'd)

Class	Soil groups	Description of profile	Reaction of profile	Soil name
	Aluvial soils			Genesee silt loam Miller clay Sharkey clay Wabash silt loam
	Saline soils	A light-colored ashy material B darker colored heavy material of columnar structure		Docas clay Fresno fine sandy loam

The texture of a soil is determined by the percentages of the particles of various size groups. As to particle size there are two grand subdivisions—those materials having diameters of 2 or more millimeters (.079 inch), which include gravel, cobbles and larger stones, and a group of materials of smaller diameter subdivided as shown in the following table:

Table 2.— Classification of soil particles as to size

Class	Diameter of particles
	mm
Gravel and stones	2
Fine gravel	1 - 2
Sand	0.05 to 1
Silt	.005 to .05
Clay	.005

The textures of soils have been defined by Marbut (16) as follows:

1. Sands include all soils containing less than 20 percent of silt and clay.
2. Sandy loams contain 20 to 50 percent of silt and clay.
3. Loams contain 20 percent or less of clay and from 30 to 50 percent of silt and from 30 to 50 percent of sand.
4. Silt loams contain 20 percent or less of clay, 50 percent or more of silt and 30 percent or less of other classes.
5. Clay loams contain 20 to 30 percent of clay, from 20 to 50 percent of silt and from 20 to 50 percent of sand.
6. Clays contain 30 percent or more of clay.

The classification of soils as to texture is shown in figure 3. This figure shows only the percentages of clay and silt; their sum subtracted from 100 gives the percentage of sand.

The A horizon, the texture of which determines the name of the soil type, is usually less than a foot in thickness and may differ in many ways from the layers below it in which pipes are usually laid. Beneath the true soil are usually one or more layers of unconsolidated material from which the soil is being slowly formed. Pipes frequently lie partly or entirely in these horizons.

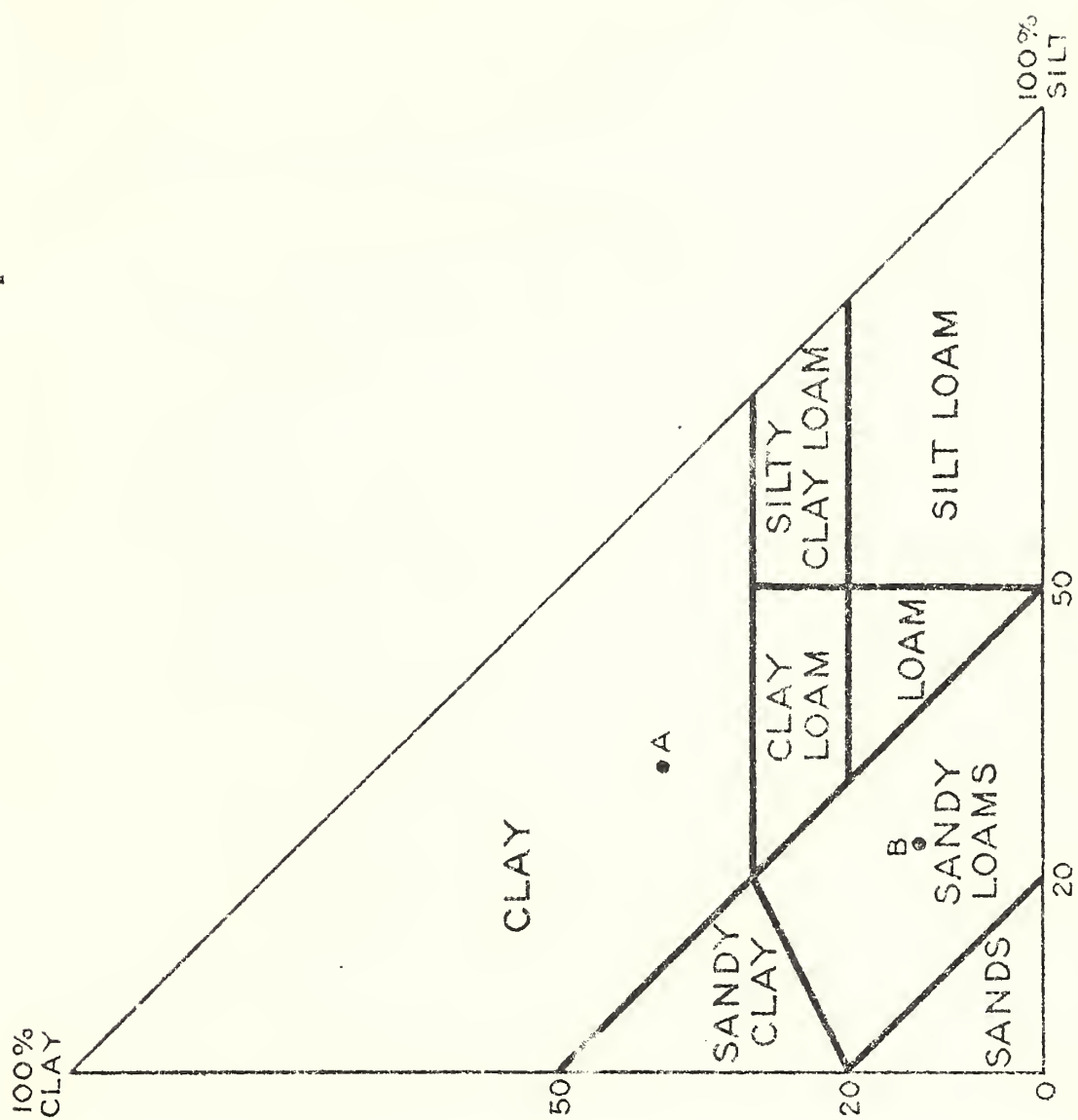


Figure 3 The Whitney diagram, showing classification of soils according to silt and clay content

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More than two hundred soil series have been named. Considerably more than one-half of the tillable area of the United States has been mapped with respect to soils. Soil reports² are issued for single counties or similar political

²Soil Survey Reports may be secured from the Superintendent of Documents, Government Printing Office, Washington, D. C.

subdivisions. Each report contains a map, which shows the location of the soil types within the area, and descriptions of the various types. The reports do not discuss the corrosivity of the soils, but some idea of their corrosivity can usually be obtained from the description of the structure and drainage of the soil and by comparison of the descriptions with those of soils in which the corrosion of pipes has been observed.

The National Bureau of Standards has conducted or supervised corrosion tests at 128 locations scattered throughout the United States. In some instances, however, two or three tests of different materials have been conducted in the same soil type. For this reason the Bureau's tests furnish information directly on only about 95 soil types. The approximate locations of these test sites are shown in table 3.

The selection of the test sites was governed to a large extent by the distribution of pipe lines and pipe networks, i.e., by the importance of the soil with respect to underground construction. Each test site represents an important soil condition, but since within an area of a few square miles several quite different soils usually exist, they are not necessarily representative of the soil conditions prevailing in the region of the site. This is illustrated by figure 4 which shows the soil series in a 6 x 7 1/2-mile area just east of Baltimore (18). Nearly all of the soil series in this area occur in more than one place and one of the soil series is represented by four soil types.

3
Table A.- Location of Bureau of Standards test sites.

Soil	Soil Type	Location
1	Allis silt loam	Cleveland, Ohio
2	Bell clay	Dallas, Texas
3	Cecil clay loam	Atlanta, Georgia
4	Chester loam	Jenkintown, Pa.
5	Dublin clay adobe	Oakland, California
6	Everett gravelly sandy loam	Seattle, Washington
7	Maddox silt loam	Cincinnati, Ohio
8	Fargo clay loam	Fargo, North Dakota
9	Genesee silt loam	Sidney, Ohio
10	Cloucester sandy loam	Middleboro, Mass.
11	Hagerstown loam	Baltimore, Maryland
12	Hanford fine sandy loam	Los Angeles, Calif.
13	Hanford very fine sandy loam	Bakersfield, Calif.
14	Hempstead silt loam	St. Paul, Minnesota
15	Houston black clay	San Antonio, Texas
16	Kalmia fine sandy loam	Mobile, Alabama
17	Keyport loam	Alexandria, Virginia
18	Knox silt loam	Omaha, Nebraska
19	Lindley silt loam	Des Moines, Iowa
20	Mahoning silt loam	Cleveland, Ohio
21	Marshall silt loam	Kansas City, Missouri
22	Memphis silt loam	Memphis, Tennessee
23	Merced silt loam	Buttonwillow, Calif.
24	Merrimac gravelly sandy loam	Norwood, Massachusetts
25	Miami clay loam	Milwaukee, Wisconsin
26	Miami silt loam	Springfield, Ohio
27	Miller clay	Bunkie, Louisiana
28	Montezuma clay adobe	San Diego, California
29	Muck	New Orleans, Louisiana
30	Muscatine silt loam	Davenport, Iowa
31	Norfolk sand	Jacksonville, Florida
32	Ontario loam	Rochester, N. Y.
33	Peat	Milwaukee, Wisconsin
34	Penn silt loam	Norristown, Pennsylvania
35	Ramona loam	Los Angeles, Calif.
36	Ruston sandy loam	Meridian, Mississippi
37	St. Johns fine sand	Jacksonville, Florida
38	Sassafras gravelly sandy loam	Camden, New Jersey.
39	Sassafras silt loam	Wilmington, Delaware
40	Sharkey clay	New Orleans, La.
41	Summit silt loam	Kansas City, Missouri
42	Susquehanna clay	Meridian, Mississippi
43	Tidal marsh	Elizabeth, New Jersey
44	Wabash silt loam	Omaha, Nebraska
45	Unidentified alkali soil	Casper, Wyoming
46	Unidentified sandy loam	Denver, Colorado
47	Unidentified silt loam	Salt Lake City, Utah.

3
Table 1 (Cont'd)

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Soil	Soil Type	Location
51	Acadia clay	Spindletop, Texas
52	Lake Charles clay loam	League City, Texas
53	Cecil clay loam	Atlanta, Georgia
54	Fairmount silt loam	Cincinnati, Ohio
55	Hagerstown loam	Baltimore, Maryland
56	Lake Charles clay	El Vista, Texas
57	Merced clay adobe	Tranquillity, Calif.
58	Muck	New Orleans, Louisiana
59	Carlisle muck	Kalamazoo, Michigan
60	Rifle peat	Plymouth, Ohio
61	Sharkey clay	New Orleans, La.
62	Susquehanna clay	Meridian, Mississippi
63	Tidal marsh	Charleston, S. C.
64	Docas clay	Cholame Flats, Calif.
65	Chino silt loam	Wilmington, California
66	Mohave fine gravelly loam	Phoenix, Arizona
67	Cinders	Milwaukee, Wisconsin
68	Gila clay	Phoenix, Arizona
69	Houghton muck	Kalamazoo, Michigan
70	Merced silt loam	Kilowatt, California
71	Mahoning silt loam ¹	Austintown Junction, Ohio
72	Trumbull clay loam	Yale, Ohio
73	Unidentified river bed	E. St. Louis, Missouri
74	Otero clay loam	Rocky Ford, Colorado
75	Unidentified alkali soil	Albuquerque, N. M.
76	Chino silt loam	Los Angeles, California
77	Susquehanna clay	Meridian, Mississippi
78	Caddo fine sandy loam	Latex, Louisiana
101	Billings silt loam ²	Grand Junction, Colo.
102	do ³	do
103	do ⁴	do
104	Cecil clay	Charlotte, N. C.
105	Cecil clay loam	Macon, Georgia
106	do	Salisbury, N. C.
107	Cecil fine sandy loam	Raleigh, N. C.
108	Cecil gravelly loam	Atlanta, Georgia
109	Fresno fine sandy loam ²	Fresno, California
110	do ³	do
111	do ⁴	Kernell, California
112	Imperial clay ³	Niland, California
113	do ⁴	do
114	Lake Charles clay	El Vista, Texas
115	Memphis silt loam	Vicksburg, Mississippi

1 The soil types of soils 71-78 are subject to change upon better identification.

2 Low alkali

3 Moderate alkali

4 High alkali

3
Table 1 (Cont'd)

Soil	Soil Type	Location
116	Merced clay	Los Banos, Calif.
117	Merced clay loam adobe	Tranquillity, Calif.
118	Niland gravelly sand	Niland, Calif.
119	Norfolk sandy loam	Macon, Georgia
120	Norfolk sand	Pensacola, Florida
121	Norfolk sand	Tampa, Florida
122	Panoche clay loam	Mendota, California
123	Susquehanna clay	Shreveport, La.
124	Susquehanna silt loam	Troup, Texas
125	Susquehanna fine sandy loam	Shreveport, Louisiana
<u>American Gas Association sites</u>		
1	Cinders	Pittsburgh, Pennsylvania
2	do	Milwaukee, Wisconsin
3	Tidal marsh	Brockton, Mass.
4	do	Atlantic City, N. J.
5	Muck	West Palm Beach, Fla.
6	do	Miami, Florida
7	Cecil clay loam	Atlanta, Georgia
8	do	Raleigh, N. C.
9	Susquehanna clay	Shreveport, Louisiana
10	Miller clay	do
11	do	Bryan, Texas
12	White alkali soil	Los Angeles, Calif.
13	Black alkali soil	do
14	Marshall silt loam	Kansas City, Missouri
<u>American Petroleum Institute sites</u>		
1	Bell clay	Temple, Texas
2	(5)	Arkansas City, Kansas
3	Lake Charles clay	Beaumont, Texas
4	(5)	League City, Texas
5	Miami silt loam	Preble, Indiana
6	(5)	Council Hill, Oklahoma
7	(5)	Caney, Kansas
8	(5)	Spindle Top Gulley, Tex.
9	(5)	Long Beach, California
10	Muscataine silt loam	Mt. Auburn, Illinois
11	(5)	Skiatook, Oklahoma
12	Merced clay loam	Mendota, California
13	Miller clay	Bunkie, Louisiana
14	Hagerstown silt loam	Chambersburg, Pa.
16	(5)	Cholame, California

5 Not determined.

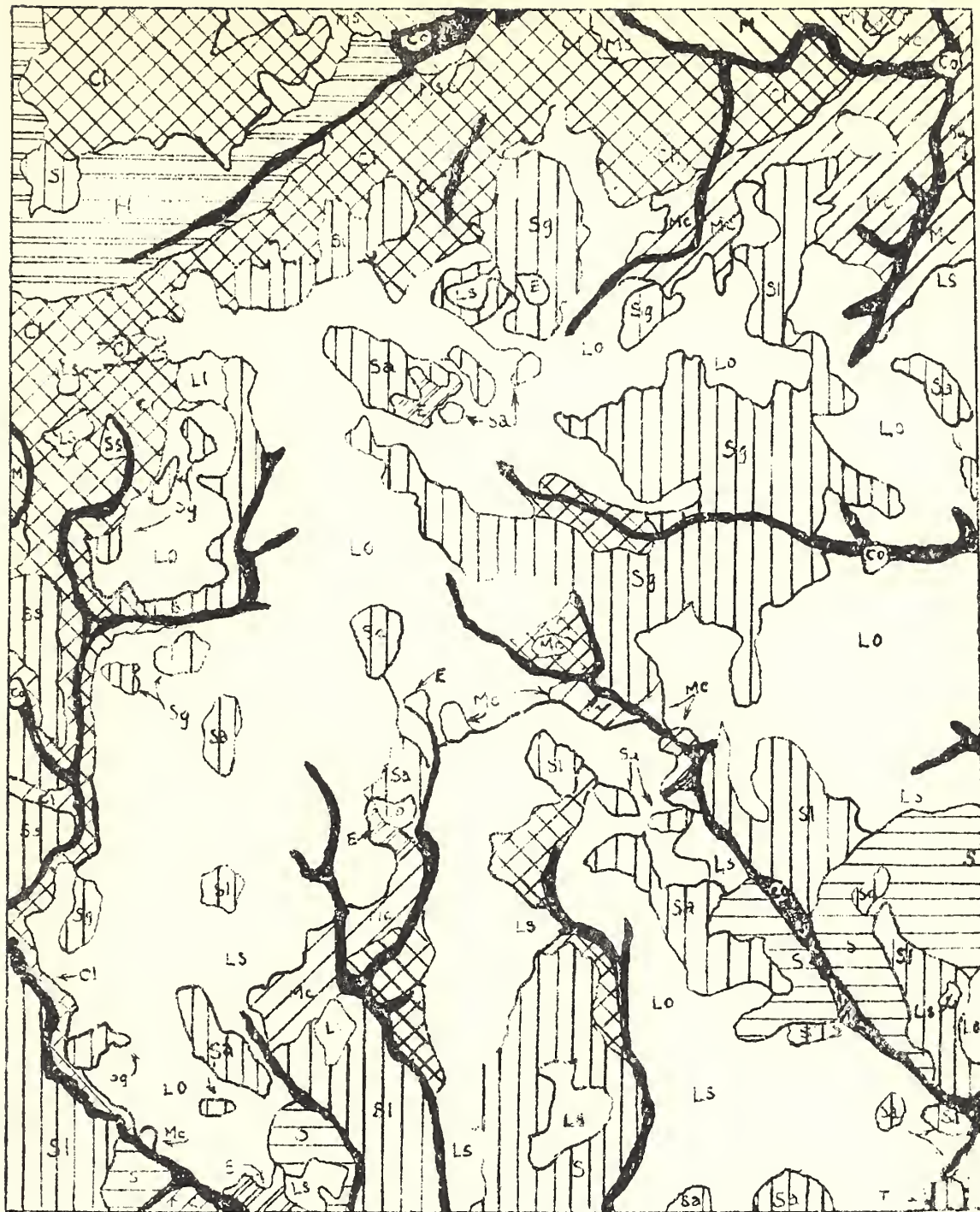
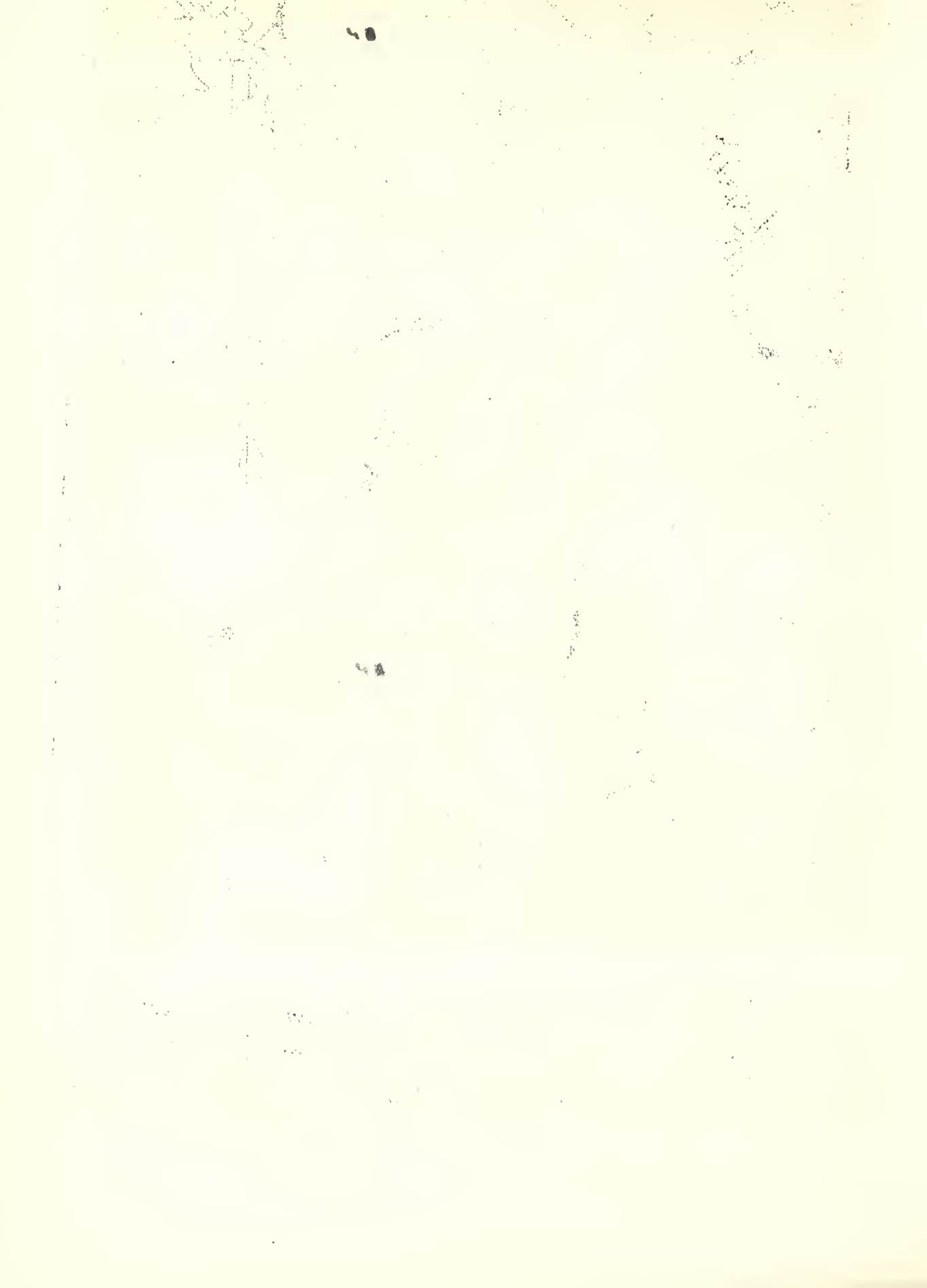


Figure 4 Soil series in a 6x7 1/2 mile area near Baltimore
 CI Chester loam H Hagerstown silt loam M Manor loam
 Co Congaree silt loam LS Gradel silt loam Mc Montebello s.l.
 E Elkton silt loam Ls Leonardstown loam S Susquehanna s.l.
 Sa, Sg, Sl, Ss Sassafraz soils T Tidal Marsh



It should be obvious that a test of materials in any one locality may not indicate the behavior of the materials in a different soil which may lie within a short distance from the test site. Moreover, since the soil horizons of a single soil may differ widely in physical and chemical properties, degree of aeration, and moisture content, a test of pipe materials in one soil horizon may yield results different from those of a test of the same materials exposed to another horizon of the same soil type. For example, the averages of the two deepest pits on five ferrous materials buried for five years in Rifle peat near Plymouth, Ohio, were 38, 37, 21, 24 and 67 mils, respectively. The corresponding values for the pit depths on the same materials exposed for seven years at the same site were 30, 34, 16, 17 and 62 mils, respectively. An examination of the site showed that the two sets of specimens were placed in two parallel trenches a few feet apart. The depths of the trenches were approximately the same, but the five-year-old specimens were laid in the peat horizon while the seven-year-old specimens were placed in the clay subsoil which was just below the peat. The surface of the ground was level, but the thickness of the peat layer varied.

2. Chemical Properties.

Although a very large number of chemical elements exist in soils, most of them are combined in difficultly soluble compounds which exert little chemical influence on corrosion. These inert components of soils are chiefly combinations of oxygen with silicon, aluminum and iron. Iron in various degrees of oxidation is responsible for the color of many soils, and this color is an indicator of the degree of aeration of the soil.

Chemical analyses of soils are usually limited to determinations of the composition of the solution resulting from the contact of water and soil under standard conditions. The bases usually looked for are sodium, potassium, calcium and magnesium. The acid radicals sought are carbonate, bicarbonate, chloride, nitrate and sulfate. Usually the hydrogen-ion concentration of the solution, or the total acidity of the soil, or both, are determined.

The development of acidity in soils is a result of the natural processes of weathering under humid conditions. In regions of moderate rainfall, soluble salts do not accumulate except where soil waters have seeped to lower levels and collected in depressions. However, in regions of high rainfall, not only have soluble salts been removed from the soil but the absorbed bases normally present in the colloidal material of

the soil have been partially removed and replaced with hydrogen ions. This process eventually gives rise to the condition known as soil acidity. The depth to which this replacement of bases has occurred varies with rainfall, drainage, type of vegetation, and nature of the material present. The fully developed soils of the prairie region have become acid to a considerable depth, while soils whose development has been retarded by poor drainage or other conditions are alkaline and may even contain appreciable quantities of salts. East of the prairies the well developed soils are acid throughout the soil profile.

3. Physical Properties.

The physical properties of soils which are of importance in corrosion are chiefly those which determine the aeration of the soil and its retentiveness for water. The texture of the soil, which is determined by the percentages of the particles of the various size groups, is obviously an important factor with respect both to aeration and moisture content. In soils of coarse texture, such as sands and gravels, in which there is free circulation of air, corrosion approaches the atmospheric type. However, in heavy clay soils, which are usually very retentive of water, corrosion proceeds in an atmosphere very deficient in oxygen, thereby tending to approach the condition of submerged corrosion. There are, however, differences between corrosion processes in water and in soil. Some of these occur because soils are much less homogeneous than water. Other differences occur because corrosion products diffuse more slowly in soils since convection currents and other movements of water are retarded by soil particles. Moreover, corrosion tests in water usually involve a single corrosive agent, whereas in soils several factors influence corrosion and may react on each other. For these reasons great care should be exercised in applying the results of tests in water to corrosion in soils.

Other properties of soils which are of importance in soil corrosion are: air-pore space, apparent specific gravity, water-holding capacity, moisture equivalent and shrinkage. The air-pore space is the percentage of the volume of soil at a definite moisture content which is occupied by air. It is therefore a relative measure of the permeability of the soil to air. The apparent specific gravity, which is the weight of a unit volume (1 cc) of undisturbed soil is an index of the compactness of mineral soils because the true specific gravity of the mineral particles in soils varies only within narrow limits. Moisture equivalent of a soil is defined as the per-

centage of water retained by a previously saturated layer of soil of given thickness when subjected to a centrifugal force of 1000 times gravity. The moisture equivalent is a measure of the retentiveness of soils for water. The quantity of water retained by soils when equilibrium with capillary and gravitational forces has been established is approximately that given by the moisture equivalent. The volume shrinkage is a measure of the colloidal nature of the dry particles in a soil. Soils which undergo large changes in volume on drying have a disruptive effect on protective coatings. The physical properties of soils are described by Keen (19). This publication, however, does not discuss the relations of the physical properties of soils to corrosion. The chemical and physical properties of soils, as well as their origin and classification, are discussed in the Atlas of American Agriculture (16) and Men and Soils (20, 21) but neither of these books discuss soil corrosivity.

IV. CAUSES OF UNDERGROUND CORROSION.

1. Characteristics of Ferrous Pipe Materials as a Factor in Corrosion.

If the surface of almost any piece of steel exposed to an electrolyte is explored with a suitable pair of electrodes and a sensitive galvanometer, a number of points will be found which differ in potential. Usually these differences are less than 0.1 volt, but they may have values of several times this amount. Some of these differences in potential are the result of unequal oxidation of the surface of the metal, mill scale, strains due to shearing or hammering, non-uniform heat treatment, different kinds of crystals in the metal, inclusions of slag or other foreign material, and segregations of metal added to improve some of the physical properties of the base metal. Some of these potential differences are accidental. Others are unavoidable. Since pipes are fabricated under carefully controlled conditions, abnormal differences of potential resulting from accidents of manufacture are relatively rare and are usually unimportant when compared with the differences of potential from other sources. An outstanding example of a potential difference resulting from the inherent characteristics of the material is that between the graphite plates and ferrite grains in cast iron. Shipley and McHaffie (22) found a difference of potential of 0.5625 volt between commercially pure iron and a graphite rod in soil water having a pH value of 7.4. Another example is the potential difference between mill scale and the iron or steel upon which it is formed in the course of the manufacturing process. Both graphite and mill scale are highly resistant to corrosion and tend to protect the metal beneath them. They tend to accelerate corrosion where they are in contact

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with the metal in the presence of an electrolyte. Speller (14) found that centrifugally cast iron, containing 3.2 percent of graphitic carbon, corroded slightly less than scale-free steel in warm aerated water.

In the majority of the Bureau of Standards soil-corrosion tests the pits on pit-cast iron are somewhat deeper than those on steel or centrifugally cast iron at the same test sites. These tests involve graphite flakes, foundry and mill scale, and several other variables. In a very limited number of soil-corrosion tests in which specimens of machined cast iron, wrought iron and steel were compared with specimens of the same materials from which foundry and mill scale had been removed, no definite effect of scale was found. The results of this limited test indicate that mill scale is not of great importance with respect to underground corrosion under severe soil conditions. Under such conditions the mill scale remains on the pipe only for a short time. In a 12-month test of wrought iron and steel in several waters, Wood (23) found no definite effect of mill scale. Thus, although graphite and mill scale are highly cathodic with respect to iron, their effects may or may not be important, depending on the conditions under which the iron is exposed.

The conclusions reached relative to the effects of mill scale and graphite on the corrosion rate probably apply also to foreign materials, inclusions and segregated materials. Ingot iron, which is commercially pure iron with less than 0.2% impurities, pitted at approximately the same rate as other ferrous materials exposed to the same soils. Whether this result was obtained because the pure iron, as well as the other wrought materials, was exposed with the mill scale on the surface has not been determined. That soil conditions rather than the nature of the ferrous materials control the rate of corrosion is suggested by the observation that the distribution of the pits is usually similar on all the commonly used ferrous materials exposed at the same test site.

Small amounts of alloying elements have generally only small effect on the rates of corrosion of ferrous metals in soils. However, the stainless steels, and iron or steel with considerable percentages of nickel, have lower rates of corrosion, especially with respect to loss of metal.

As might be expected, non-ferrous metals differ from iron and from each other in their potentials with respect to a reference electrode in adjacent soil and hence with respect to corrosion. Their relative merits for service underground will be discussed in the section dealing with the prevention of corrosion.

2. Effects of the Chemical Properties of Soils.

The soluble constituents of soils affect corrosion because they control the potentials of the anodes and cathodes and the resistance of the path of the corrosion current. The soluble constituents, especially the salts, furnish most of the ions which carry the current. As a rule, soils containing considerable quantities of salts in solution are corrosive.

Corrosion is also affected by the reactions between the soluble salts and the primary products of corrosion, the effect on the corrosion rate depending on whether the reaction products are precipitated and on the location of the deposited products with respect to the anode and cathode of the corrosion circuit. In general, if the reactions result in the formation of soluble products, or if the products are precipitated at a distance from the electrodes, corrosion continues.

If insoluble, poorly conducting products are deposited on one or both of the electrodes, corrosion will be retarded. For example, iron continues to corrode in soils containing sodium chloride because the anodic corrosion product, ferrous chloride, and the cathodic product are both soluble. On the other hand, if calcium bicarbonate is present, difficultly soluble calcium carbonate is precipitated at the cathodic areas because of the increase in alkalinity in that region resulting from the flow of current. As a result of this deposit the current is reduced and the rate of corrosion decreases.

If iron is placed in a soil containing a soluble sulfate, corrosion progresses as in the presence of sodium chloride, but if lead is substituted for iron, corrosion ceases after a short time because of a deposit of insoluble lead sulfate.

The corrosiveness of soils is, in general, indicated by the chemical composition of the soluble material in the soils. Soils containing high concentrations of soluble salts, particularly of sodium and potassium, are usually very corrosive to ferrous metals. However, when the soluble material consists largely of calcium and magnesium bicarbonates, corrosion is relatively slight because of the formation of protective deposits of corrosion products. Table 4 shows the composition of the water extracts from five of the least corrosive soils in the original Bureau of Standards soil-corrosion tests and from five of the most corrosive soils in the same tests. The table also shows the maximum pit depths on the 12-year-old Bessemer steel specimens exposed to these soils, and the electrical resistivity of the soils.

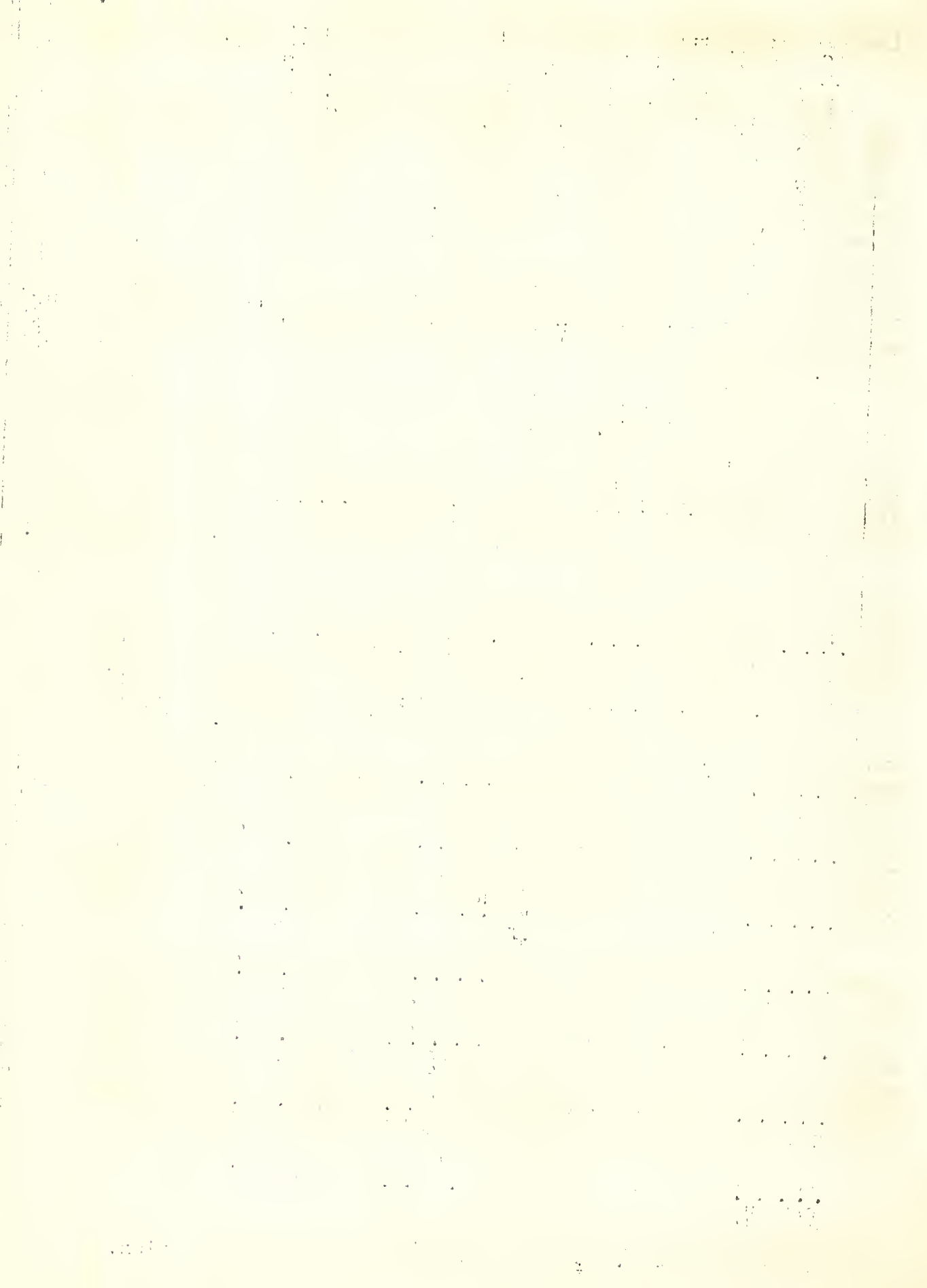
Table 4.— Chemical properties of soils.

Soil	Corrosivity Max pit Life depth 12 yrs mils	Elec. resistivity ohm cm	Acidity		Composition of water extract mg equivalent/100 gr soil						
			pH	Total	Na+K as Na	Ca	Mg	CO ₃	HCO ₃	Cl	SO ₄
No.	Series										
Least corrosive with respect to max pit on 126 sq in. of Bessemer steel at 12 years											
47	Unidentified	29	7.6	3	0.67	0.72	0.39	0.00	0.88	0.06	0.48
24	Merrimac	31	4.5	12.6	(a)	—	—	—	—	—	—
26	Miami	39	7.3	2.6	.27	.50	.31	.00	.70	.03	.12
6	Everett	40	5.9	12.8	—	—	—	—	—	—	—
31	Norfolk	45	4.7	1.8	—	—	—	—	—	—	—
Most corrosive with respect to max pit on 126 sq in. of Bessemer steel at 12 years											
23	Merced (alkali)	173	9.4	(A)	8.38	0.38	0.22	0.02	1.87	1.12	5.57
28	Montezuma (alkali)	153	6.8	—	1.50	.06	.18	.00	0.12	0.99	0.89
29	Muck	146	4.2	28.1	2.15	1.92	1.55	.00	.00	1.69	2.30
45	Alkali soil	137	7.4	(A)	8.15	3.70	0.70	.00	.24	0.18	11.98
8	Fargo	119	7.6	(A)	1.42	1.72	2.55	.00	.71	.01	4.43
Least corrosive with respect to life of 1000 feet of 8-inch steel pipe based on Ewing's equation											
31	Norfolk	—	4.7	1.8	—	—	—	—	—	—	—
6	Everett	—	5.9	12.8	—	—	—	—	—	—	—
24	Merrimac	—	4.5	12.6	—	—	—	—	—	—	—
36	Ruston	—	4.5	4.6	—	—	—	—	—	—	—
17	Keyport	—	4.5	19.1	—	—	—	—	—	—	—
Most corrosive with respect to life of 1000 feet of 8-inch steel pipe based on Ewing's equation											
29	Muck	7	4.2	28.1	2.15	1.92	1.55	0.00	0.00	1.69	2.30
23	Merced (alkali)	8	9.4	(A)	8.38	0.38	0.22	.02	1.87	1.12	5.57
28	Montezuma	—	6.8	—	1.50	.06	.18	.00	0.12	0.99	0.89
45	Alkali soil	—	7.4	(A)	8.15	3.70	0.70	.00	.24	0.18	11.98

a not determined

b A = alkaline

See reference 2 for discussion of Ewing's equation.



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Rates of corrosion are affected by the time of exposure and the area of the specimen exposed as will be discussed later. The material that is the most seriously corroded after a short exposure may last longer than another material exposed to the same soil. For this reason table 4 also includes five of the least corrosive soils and five of the most corrosive soils based on the estimated time required for 1000 feet of 8-inch steel pipe having a wall thickness of 0.322 inch to develop a leak due to corrosion. The paper² from which the data were taken indicates that the estimates are very rough. It will be noted that the corrosive soils are considerably lower in resistivity and higher in salt content than the less corrosive soils.

The effect of acidity on the corrosion of ferrous metals in soils and in natural waters is much the same as that of salts such as sodium chloride, since the effect in both cases is to increase the solubility of the corrosion products. Baylis (24) has pointed out that the tendency of iron to go into solution would be a function of the H-ion concentration if there were rapid displacement of the solution and no tendency to form a surface coating. Whitman, Russell and Altieri (25) and Whitman and Russell (26) found that in a solution free from salts which form protective coatings, the corrosion rate of steel was unaffected by the H-ion concentration between pH 9.5 and pH 4, but was determined by the rate at which oxygen diffused to the cathodic surface, and by the protectiveness of the film formed on the metal surface. The protective action of this film in water having a pH as low as 4 was attributed to the fact that the quantity of hydrogen ions coming in contact with the metal surface was insufficient to neutralize and dissolve the film. However, when carbon dioxide was introduced rapid corrosion occurred at pH 5.4 because then the increased total acidity of the water was sufficient to neutralize the hydroxide film. This result led to the conclusion that total acidity is more important in corrosion by natural waters than is the actual concentration of hydrogen ions, i.e., the pH value.

As the acids present in soils are only slightly dissociated, the pH value of a soil may offer no indication of the capacity of the acidic material to prevent the formation of otherwise protective hydroxide films. An acid soil having a relatively high pH value and a high total acidity would be expected to be more corrosive than a soil having a lower pH value and a lower total acidity because of the greater tendency of high total acidity to prevent the formation of protective films. Denison and Hobbs (27) found a correlation between

total acidity and the corrosiveness of soils with respect to steel both in the field and in the laboratory under conditions in which other causes of corrosion were nearly constant. This correlation was confirmed by Denison and Ewing (28) who obtained the correlation shown in table 5 between total acidity and replacements for a pipe line in Ohio. It will be noted that in the absence of other variables the corrosiveness of the soils increased with their acidity. However, the standard deviation of the average percent of replacements shows that even within a single type of soil the corrosion varies greatly.

Table 5. -- Relation of acidity to repairs in soil types.

Soil type	Total acidity	Standard error	Repairs	Standard error per body	Standard deviation
	mg. eq.	percent	percent	percent	percent
Wauseon fine sandy loam*	7.5	--	6.3	--	--
Caneadea silt loam	12.7	1.6	13.3	2.3	11.0
Miami silt loam	16.3	2.8	22.8	6.6	22.8
Mahoning silt loam	18.1	0.7	20.9	3.6	13.3
Trumbull clay loam	21.1	2.3	20.0	5.1	10.3
Crosby silt loam	22.0	1.2	30.8	3.8	16.9

*One sample

3. Effect of the Physical Properties of Soils.

Corrosion is retarded by the oxidation of corrosion products which produce films or thicker deposits. Those deposits either reduce the differences of potentials between anodic and cathodic areas or interpose electrical resistance which reduces the corrosion current. The degree to which oxidation occurs depends largely on how readily oxygen can reach the corroding metal, which is determined by the permeability of the different soil horizons both above and below the buried metal, and the rainfall and drainage of the region. In general, the aeration of clay soils is poor, while that of sandy soils is usually good. However, low-lying sands, and sands underlain by a consolidated stratum or a hard pan layer, may be poorly aerated for long periods in regions where the rainfall is heavy.

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Since the aeration of the soil, which is the chief factor in the supply of oxygen and carbon dioxide, is determined not only by the character of the soil but also by the water which the soil contains, the aeration will vary from season to season and cannot be expressed exactly or numerically except perhaps for some transient condition.

In well aerated soils the rate of pitting of ferrous metals is initially very high because of the abundant oxygen supply at the cathodic areas. However, oxidation and consequent precipitation of the corrosion products in close contact with the anodic areas cause a marked reduction in the corrosion rate, with the result that the ultimate depth of pitting is relatively slight. On the other hand, in poorly aerated soils the rate of pitting, although low because of deficiency of oxygen at the cathodic areas, is relatively unchanged with time, because the corrosion products in the reduced condition are precipitated at points remote from the anodic areas. Consequently, the depths of the deepest pits after a long period are usually considerably greater in poorly aerated soils than in well aerated soils.

Some soil water occupies the larger spaces between the soil particles, holes left by decaying roots, etc. This part of the soil moisture varies greatly with the season, rainfall and drainage. Water also adheres closely to the minute soil particles, and is removed from them and the small soil capillaries only with difficulty. On this account well drained soils retain a certain amount of moisture through long periods of drought. There is a tendency for corrosion to increase with the moisture equivalent of the soil, but this tendency may be obscured by other factors.

The air pore space is a physical characteristic of soils which depends on the texture of the soil and other properties. For well drained soils the air pore space indicates the supply of oxygen at any given depth and the rate at which moisture can move through the soil. Other things being equal, a high value of air pore space indicates a non-corrosive soil. The apparent specific gravity of the soil is influenced to a large extent by the amount of voids in the soil.

The volume shrinkage of soil indicates the tendency of the soil to crack on drying and to swell when wetted. The cracking of soil permits more oxygen to reach buried pipe and so affects the character of the corrosion products and the differential aeration potentials. Some soils on drying form hard clods which at times act much like stones with respect to differential

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aeration and pressure on pipe coatings. Some soils adhere tightly to some pipe coatings, and as they shrink on drying tend to pull the coating from the pipe (29). Some coatings are pressed into the soil cracks when the soil expands due to the absorption of water. Thus soil shrinkage is important to corrosion and pipe-line protection. In general, clay soils and soils high in organic matter shrink the most, but not all clay soils shrink greatly on drying. For example, Bell clay has a clay content of 44.9 percent and a shrinkage value of 23 percent while Susquehanna clay has a clay content of 45.8 percent and shrinks only 4.7 percent. Fargo clay loam has a clay content of 70.1 percent and a shrinkage of 21.0 percent.

The physical characteristics of soils which are favorable to corrosion are poor aeration, and high values for moisture equivalent, clay content, apparent specific gravity and shrinkage. These are characteristics of heavy, poorly drained soils. They are not independent of each other and their effects on corrosion may be modified by the chemical characteristics. Table 6 shows the relative corrosivity of some of the soils in the Bureau of Standards tests as indicated by the average of four criteria, and the values of some of the physical properties of those soils.

Although there is no close correlation between the corrosivity of the soils and any one soil property, the table supports the summary of the effects of the physical properties given above.

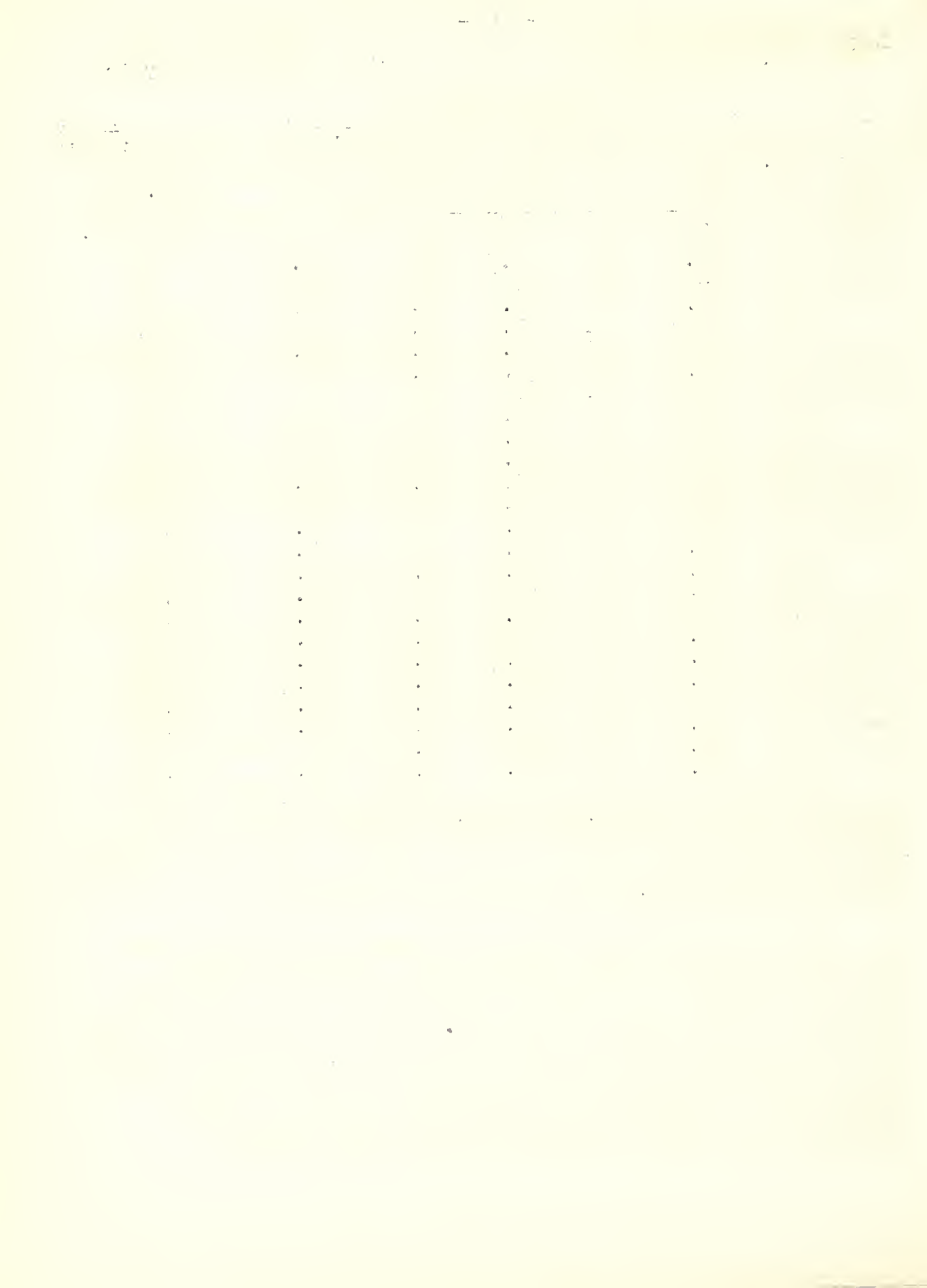
Table 6. -- Correlation of soil corrosivity with the physical properties of soils.

Relative corrosiveness	Soil No.	Moisture equivalent	Aeration ¹	Air pore space	Apparent specific gravity	Volume shrinkage	Resistivity at 60°F (15.6°C)
		%		%	%	%	ohm-cen.
1	228	19.6	VP	2.5	3(b)	5.9	408
2	43	34(b)	VP	(b)	3(b)	3(b)	60
3	14	12.2	F	14.4	1.76	1.0	3,520
4	4	29.9	P	7.0	1.78	2.2	6,670
5	40	31.0	P	2.3	1.78	16.4	970
6	42	24.8	F	14.9	1.79	4.7	13,700
7	37	7.0	F	3(b)	3(b)	0	11,200
8	8	34.8	P	8.7	1.56	21.0	350
9	11	31.3	G	15.5	1.49	8.6	11,000
10	16	16.5	F	12.0	1.65	0.6	8,290
11	39	18.3	P	7.5	1.72	3.8	7,440
12	41	28.1	F	6.9	1.61	14.6	1,320
13	44	25.3	G	7.2	1.55	6.0	1,000
14	3	29.9	G	18.2	1.60	7.0	30,000
15	30	24.0	P	7.2	1.81	7.5	1,500
16	32	11.8	G	11.7	1.85	0.1	5,700
17	19	26.3	F	3.9	1.76	11.8	1,970
18	2	35.2	P	2.0	1.95	23.0	684
19	22	28.4	G	9.6	1.67	3.0	5,150
20	18	22.0	G	16.6	1.26	1.3	1,410
21	25	18.6	F	9.5	1.95	7.6	1,780
22	7	36.4	P	3.7	2.02	34.5	2,120
23	36	14.9	G	16.0	1.62	0	11,200
24	17	27.7	P	4.4	1.72	5.4	5,980

1 VP = very poor; P = poor; F = fair; G = good

2 Most corrosive soil

3 (b) = not determined.



4. Stray Currents.

The effects of stray electric currents from direct-current power plants and their mitigation is too large a subject to be adequately treated in this paper. The principles involved are covered in two publications (30, 31), both of which were published when stray-current electrolysis was a more frequent cause of corrosion than it is at present. Methods of detecting stray currents have also been described (32, 33).

Serious corrosion is not caused by induction from power lines. Alternating current does not ordinarily cause corrosion (34, 35, 29), but under some conditions alternating currents may stimulate corrosion (9).

Corrosion from stray currents is most prevalent in the neighborhood of direct-current street railways, power houses and substations; but occasionally it occurs in regions remote from these sources of power because of an exchange of current between underground structures.

Stray street-railway current can usually be identified by irregular fluctuations which are the result of the acceleration of street cars. Measurements of difference of potential between two points on a metallic structure or between the structure and the adjacent earth made with a suitable millivoltmeter will usually determine whether stray currents are present. The discovery of the source of the current and the remedy for it is usually a difficult problem which can best be left to someone experienced in this line of work.

Recently the application of cathodic protection to pipe lines has introduced a new source of stray currents. The prevalence and seriousness of this cause of corrosion differs greatly in different parts of the country. Corrosion resulting from cathodic protection can best be eliminated by the cooperation of the utilities having adjacent pipe lines.

In the investigation of stray-current electrolysis it is well to remember that, except for a possible heating effect, current on a metallic structure does not injure it. Corrosion occurs only at points where current flows from the structure to the earth. For this reason the potential of the structure with respect to the adjacent earth determines whether or not corrosion can occur at the point of observation. The potential of the pipe in question with respect to other structures is immaterial to corrosion, although it may indicate the source or carrier of the stray current.

5. Long-Line Currents.

Closely related to stray currents from street railways are so-called long-line currents. If a sufficiently sensitive millivoltmeter is connected across a few feet of almost any pipe line, a deflection will be obtained indicative of a flow of current along the line (36). The currents vary in magnitude under different conditions and usually do not exceed a few amperes. The source or cause of these currents has been variously explained. Gish (37) associates them with magnetic storms. Putnam suggested that they may be caused by charges of electricity collected from the air by oil storage tanks or to the interaction of different soils. Shepard (38), Mudd (39) and Weidner and Davis (40) have found rough correlations between long-line currents and pipe-line corrosion, but Gill and Rogers (41), after a study of 9 miles of a single pipe line, decided that these currents did not influence corrosion. Stirling (42), after studying currents on 650 miles of pipe line, concluded that long-line currents were not of such magnitude as to cause deterioration of pipe lines, but they are indicators of the location of corroded pipe.

Since most observers have made no attempt to determine the density of the current leaving the pipe, it could not be expected that they would find any close relation between the currents and the depths of the pits on the pipe. The seriousness of the corrosion caused by the discharge of current is determined not by the total quantity of current discharged, but by the quantity discharged at the area where the current density is greatest. A very small current discharged from a very small area may result in a very deep pit of small diameter while a large current discharged from a large area may remove much more metal without seriously affecting the strength or usefulness of the pipe.

Under average conditions one might expect that the discharge of long-line current would be distributed over a considerable amount of pipe surface, as was indicated by the data in one of the papers (36) referred to. Consequently serious damage to pipe would not be expected to be caused by such long-line currents as have been reported.

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Long-line currents on pipe lines near pump stations usually flow into the storage tanks with which the lines are connected. This is probably because of the restricted amount of oxygen which can reach the tank bottom, although it might be due to the fact that the material of the tank bottom is slightly different from that of the remainder of the tank. Usually the area of the tank bottom is so large that the density of the current leaving it and the resultant rate of corrosion are very small. However, corrosion of tank bottoms is occasionally sufficiently serious to call for the application of cathodic protection (43).

6. Bacteria.

The best known species which affect corrosion are the sulfate-reducing bacteria, *Spirovibrio desulfuricans* (3) (11). These bacteria are prevalent in many soils and have been found at great depths in wells. Their activity requires some form of a sulfate and organic material. They are said to be active only in nearly neutral solutions free or nearly free from oxygen. In the life processes of these organisms, sulfates are reduced to sulfides and hydrogen is removed from the cathodic areas on the pipe exposed to the bacteria. Authorities differ as to the details of the mechanism by which the hydrogen is removed and sulfides produced, but the net result seems to be acceleration of corrosion in two ways: (1) the depolarization of the cathodic areas and (2) the acceleration of corrosion at the anode by hydrogen sulfide. The activity of these bacteria may be recognized by an abnormal amount of iron sulfide in the corrosion products and by the odor of hydrogen sulfide when dilute hydrochloric acid is added to the corrosion products. It is also possible to prepare cultures of the bacteria and to recognize their presence by the use of a microscope or by the blackening of iron placed in the culture.

The presence of bacteria in corrosive soils has been demonstrated and may account for the observed corrosion. It may also explain some failures in soils classified by the usual tests as "not corrosive". However, no correlation has been found and no methods developed for measuring this effect.

The bacteria discussed above are anaerobic and thrive only in soils nearly free from oxygen. According to Beckwith (12), there are also some aerobic bacteria which may cause or accelerate corrosion.

7. Conditions Incidental to Pipe-Line Construction.

The methods used in the construction of pipe lines are the indirect causes of much of the corrosion of the lines. Some of these causes are unavoidable. The elimination of others may be more expensive than the losses they cause. Other causes may be avoided at little expense if they are recognized by those responsible for the laying of the line.

a. Causes of corrosion incidental to backfilling.

One of the most prevalent causes of corrosion of cross-country lines is differential aeration resulting from the way in which the soil is replaced in the trench. Heavy soils frequently form large hard clods when they dry out after being removed from the trench. When these are scraped back by a bulldozer or other machine, voids are formed beneath the lower shoulder of the pipe which persist for long periods. Other voids occur between clods which meet along the upper shoulders of the pipe, while still others occur because of the unevenness of the trench bottom and because of bends in the pipe. Differential aeration also occurs when more porous soil particles fill spaces between the denser clods. It has already been pointed out that comparatively high potential differences may result from differential aeration. Potential differences also result from backfilling with soils from horizons differing in texture and chemical composition. Some pipe-line operators have avoided these causes of corrosion by placing a layer of sand next to the pipe. Others use water or tamp the backfill, but these measures are usually adopted to avoid settling of the backfill, and any mitigation of corrosion is incidental.

Occasionally serious corrosion has occurred because of stones, sticks or other foreign material which were allowed to come in contact with the pipe when the trench was back-filled.

b. Potential differences between soils and between soil horizons.

Inspection of almost any soil-survey map, figure 4 for example, will show that within a few miles a pipe line may traverse several soil series. These soils may differ widely in many of their properties, such as chemical composition, texture, moisture content and aeration. In much the same way the pipe line may encounter different soil horizons because it is not laid at a uniform depth below the surface of the ground or because the soil horizons vary in thickness or

because the diameter of the pipe is large. The different soils or soil horizons may differ in their potentials with respect to the pipe and so cause corrosion. It would be difficult to determine whether these potential differences were the result of differences in chemical composition of the soils or differential aeration resulting from differences in texture or moisture content.

c. Interconnection of different metals.

As has been indicated, a difference of potential exists between almost any two metals or between two varieties of the same metal. In the case of some combinations of ferrous and nonferrous metals the difference of potential is large. Whether serious corrosion occurs depends on the reactions which take place. In many cases an oxide or other film forms on one of the metals and prevents serious corrosion. In other cases the area of the anodic material is so large in comparison with the cathodic area that either the corrosion is distributed over a large area or cathodic polarization reduces the corroding current to a negligible quantity. It is standard practice to screw brass corporation cocks into cast iron water mains, and little or no corrosion has resulted from the practice. A few cases of corrosion of steel attached to copper service pipe have been reported.

Serious corrosion of iron parts of valves with brass seats exposed to rapidly flowing sea water has occurred. In this case it seems probable that the movement of the water depolarized the cathodic metal.

The relative positions of two metals in the electromotive or electrochemical series is not a dependable criterion for the extent of the corrosion resulting from the contact of the two metals in an electrolyte such as soils or natural waters. It is advisable, however, insofar as other conditions permit, to avoid metallic contacts between metals far apart in the series if the joint is exposed to an electrolyte.

d. Interconnection of old and new pipe.

Especially in the transportation of petroleum it is customary to supplement the pipe line first laid with newer parallel lines, all the lines being metallurgically connected at the pump stations. Measurements have shown (36) that if an old pipe line is paralleled by a newer line, the newer line will remain anodic to the older line for several years at least, if the two lines are interconnected. Interconnection

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of the two lines evidently accelerates the corrosion of the newer line and tends to prolong the life of the older one. This may explain some cases in which the original line outlasted a newer line which paralleled it. In most cases the current flowing from the newer line is discharged from so much of its surface that the corrosion on this account is not serious.

V. IDENTIFICATION OF CORROSIVE SOILS.

The identification of corrosive soils may be undertaken for two different, although related, purposes: (1) to determine whether the character of a sample of soil from a selected spot is such as to account for the corrosion observed at that spot and (2) to determine whether the soils along a pipe-line right-of-way are sufficiently corrosive to justify the application of protective measures to an actual or proposed pipe line. The study of individual samples of soil will be discussed under the heading "Soil Tests" and the more extended investigation under the heading "Soil Surveys". It should be noted that both of these studies assume that some soil properties are responsible for the corrosion observed or anticipated. It follows that the results of the studies can be satisfactory only insofar as the assumption is correct.

1. Soil Tests.

The earliest tests for the corrosivity of soils were probably chemical analyses of soils or soil extracts. In regions where the rainfall is moderate or high, the soluble material remaining in the soil is very limited and chemical analyses have thrown little light on the cause of corrosion except in cases of contamination by factory waste or some similar cause. In the more arid regions some of the soils contain considerable percentages of soluble salts, and chemical analyses of soils of these regions have been more useful. Since the electrical conductivity of the soil depends in part on the concentration of soluble salts, measurements of electrical conductivity or resistivity are widely used in locating soils that are corrosive with respect to iron. These measurements do not differentiate between the salts in the soil and therefore do not take account of their film-forming properties. Soil-resistivity measurements probably would not indicate the corrosivity of soil with respect to lead.

The earliest apparatus for this purpose was probably the electrolytic bridge (44). This method was developed for determining the quantity of salts in soils rather than for determining soil corrosivity, and it has not been used extensively for the latter purpose. Based chiefly on the conductivity of the soil, but bringing into consideration some other factors is the Williams-Corfield nipple-and-can test (45), which is extensively used especially on the Pacific Coast where it was developed. According to this method a weighed 4-inch length of $3/4$ -inch iron pipe is placed vertically in the center of a tin can 3 inches in diameter filled with the soil to be tested in a saturated condition. A 6-volt battery is connected between the pipe and the can for 24 hours, and the loss of weight is determined. Corfield compared the losses determined in this way with the relative corrosivity of soils taken from locations where he had measured pit depths, and so calibrated his apparatus in terms of probable pipe life.

More recently Denison (1) (46) developed an electrolytic method for testing soils which is somewhat less arbitrary and includes a larger number of variables. The method has been used extensively at the Bureau of Standards and to a slight extent elsewhere. It requires somewhat more apparatus than other methods and requires more time than some of them. The method has been modified from time to time.

5 One of the most important weaknesses of all soil tests is the inadequacy of the sample. If a single small sample is tested, the best result that can be hoped for is the corrosiveness of the sample. This may or may not be representative of any considerable amount of soil, and in many tests the physical condition of the sample is not that of the soil to which the buried metal is exposed. If a large sample is tested, or if a large number of samples are taken and mixed or tested separately, the final result at best represents the average corrosiveness of the samples, and in the case of the latter procedure, the dispersion of the individual results with respect to the average. The same line of reasoning is applicable to the tests of materials by exposing them to soils. By tests of soils or of materials exposed to soils a rough idea of corrosiveness or resistance to corrosion may be obtained, the reliability of which depends on the extent to which conditions of the test are representative of field conditions. As bases for predictions of average field results, adequate test results are of great value, but they are unreliable as indications of what will happen in any individual case of exposure of metal to soil unless the test and the exposure conditions are known to be identical in all essential respects.

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2. Soil Corrosivity Surveys.

A soil corrosivity survey may be made to ascertain whether a pipe line already laid is corroding seriously at certain points or to determine what sections of a line laid or projected should be protected against corrosion. It is accomplished by a series of tests of samples of soil selected as representative of conditions both as to extent and corrosivity. Its usefulness depends to a large extent on the accuracy of the sampling in these respects, and frequently too little attention is paid to this question. The same soil types frequently occur at several places along a long pipe line or right of way and the number of tests may be reduced by first determining the location and extent of each soil type and then obtaining an adequate number of samples from each type instead of taking samples at equally spaced intervals. It will usually be found, as shown by table 5, that some soil types are corrosive while others are not. Under such conditions a coating or reconditioning policy for a pipe line is preferably based on the soil type as the unit. If the coating or reconditioning of a line is limited to a few types of treatment, it is usually sufficient to divide the soils into a somewhat larger number of groups with respect to corrosiveness.

Since the group boundaries are arbitrary and each soil merges into the adjoining soils, it is frequently considered that a soil test is satisfactory if it comes within one group of placing the tested sample in the correct group, that is, if the soil actually belongs in group three with respect to corrosiveness the purposes of the survey will have been accomplished if the test places the sample in group two, three or four. However, a satisfactory corrosion test should assign the majority of the soils to the correct group.

Since it is unusual in many parts of the country to find any one soil series extending continuously in one direction for a distance of a mile, and since many pipe lines or sections of lines extend a hundred miles or more, a soil survey to be adequate must involve a large number of tests. It follows that the time required for a single test is an important consideration. Usually a large number of approximately correct results are more useful in the protection of a long line than a few accurate results, because a single test usually shows the condition of only a small part of the line.

The Shepard soil-resistivity meter (38) is probably the instrument most frequently used for soil-survey work because of its low cost, simplicity, and the speed with which measurements can be made. The apparatus consists of two small steel electrodes on the ends of insulating rods. The rods are thrust into the soil to the depth at which the resistivity of the soil is desired. This is usually accomplished through the use of a soil auger or a steel bar driven into the soil unless a trench is available. Between the electrodes is connected a milliammeter and a small dry cell. The milliammeter is calibrated in terms of the voltage of the cell divided by a constant times ^{only} the current, i.e., in terms of resistivity. The instrument ~~measures~~ ^{only} measures roughly the resistivity of the soil near the electrodes at the time of the test. For this reason a large number of tests should be made. If the soil is very dry or gravelly the results are unsatisfactory. If the resistivities of the soils are high, say above 1000 ohm-centimeters, a decrease in resistivity may be more indicative of a corrosive area than the magnitude of the resistivity. Usually soils having resistivities less than 500 ohm-centimeters are seriously corrosive, either because they are wet or because they contain large percentages of salts in solution. There are several other instruments which measure soil resistivity with greater accuracy. However, the relation between soil corrosivity and resistivity is not close enough to justify any considerable expenditure of time or labor in order to obtain better than approximate values of resistivity.

The extent to which individual determinations of soil resistivity correlate with the maximum pit depth observed on a pipe adjacent to the test site is illustrated by figure 5. The wide range of pit depths might be explained by saying that the shallower pits were of more recent origin, which may or may not be true. There is a slight trend toward deeper pits with decreasing soil resistivities but even this trend is not very well defined. The data were obtained along 25 miles of 8-inch pipe in eastern Texas and it will be noted that most of the resistivities are above 500 ohm-centimeters. It is probable that data taken in a more arid region where alkali soils are prevalent would yield a better correlation.

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Similar correlations for seven other methods (47) for determining the corrosivity of the soil were obtained. The poor correlations resulting from all methods of testing soil corrosivity suggest that the condition of the pipe is affected, if not controlled, by factors other than the property of the soils which determined the result of the test.

That soil tests roughly classify soils as to corrosiveness is shown by table 7. The soils in the inspections just referred to were arbitrarily divided into five groups with respect to corrosiveness as indicated by pit-depth measurements. The corrosiveness of the soils as determined by each test was also divided into five degrees of intensity. The extent to which each test placed each soil in its proper group with respect to its corrosiveness is shown in table 7. As some of the soils were represented by only a few samples and a few lengths of pipe, a close correlation of the results of the tests with pit depths could not be expected in all cases. If, as was suggested earlier in the paper, an assignment of corrosivity within one step of the correct assignment is **considered satisfactory** for practical purposes, it will be seen that nearly all of the tests were reasonably satisfactory and several were almost equally effective.

VI. CRITERIA FOR CORROSION AND CORROSIVITY.

1. Basis for Determining Corrosion.

Comparisons of the corrosiveness of soils and the resistances of materials to corrosion are unsatisfactory partly because there is no recognized standard. As might be expected, different bases yield different results. Among the criteria are loss of electrical conductivity, loss of strength, time required for corrosion products to become visible, maximum or average penetration, time required for the development of a leak in a container such as a pipe, and life of pipe or other structure.

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Table 7.- Effectiveness of corrosivity tests in classifying soils as to corrosivity

Soil Series	Percent of Line	Shepard Resistivity Meter	Resistivity at Moisture Equivalent	Total Acidity	Acidity Times 1,000 Resistivity	Modified Columbia Putnam Rod Test	Nipple- and-Can Test	Denison Electrolytic Cell
Acadia	12.96	0	0	+1	+1	+1	+1	0
Brown	0.38	+1	+2	-2	-1	0	0	0
Caddo	24.43	0	0	+1	0	0	+1	0
Conglomerate	2.59	-2	0	-3	-3	-1	0	0
Crowley	2.20	-1	+1	0	0	-1	-2	0
Dark brown	0.98	0	+2	0	0	0	0	0
Lake Charles	34.32	-1	+1	-1	+1	0	-2	0
Leaf	8.73	0	+1	+3	+2	0	0	0
Light gray	1.16	0	0	-4	-1	0	0	0
Myatt	4.51	+2	+4	0	+1	+1	0	+2
Ochlockonee	0.88	0	+1	0	+1	0	0	0
Segno	6.85	0	+1	+3	-1	-1	0	0
Percent of soils	58	Percentages of Correct Assignment						
Percent of line	56	33	33	15	25	58	75	92
Percentages with an Error of not more than One Corrosion Group								
Percent of soils	83	75	58	83	92	92	83	92
Percent of line	93	94	86	89	97	95	63	95

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Study of these proposed measures of corrosion shows that most of them require some rather arbitrary specifications which limit their applicability to a circumscribed field. For sewer pipes and culverts crushing strength is of primary importance, and small isolated pits or punctures have little immediate significance. For lines carrying oil, water, or gas, pits are unimportant except insofar as they indicate how soon leaks are to be expected, and this can not be estimated from pit depths alone. The importance of a leak depends on the cost of repairing it and the damage resulting from it. Different companies estimate the cost of a leak from fifty to more than a thousand dollars. The life of a pipe may be the time required for the development of a single leak in a unit length or the time required for its condition to be such that additional repairs would be unprofitable. Many pipe-line operators maintain that although sections of a pipe line may require repairs or renewal, the life of the line as a whole is limited only by the need for the line.

For purposes of valuation the condition of a pipe line is frequently expressed as a percentage of the value of a new line. Here again there is a difference of opinion and a distinction between present value or usefulness and the length of time the usefulness will continue. Some operators contend that the purpose of a pipe line is to conduct a fluid, and that so long as a line will do this without a decrease in carrying capacity, the value of the line is not affected by the extent to which it is corroded.

2. The Effect of Time and Exposed Area on the Relative Merits of Materials

It has already been explained that rates of corrosion change with the period of exposure and that the change in rate is different for different materials and for different conditions of exposure (48). On this account, rates of corrosion, however expressed, have little usefulness if materials are to be compared. An analogous situation exists with respect to the relation of maximum pit depths, leaks, or life of pipe to the area of the specimen or pipe under consideration (2). Since corrosion is far from uniform, the greater the exposed area the shorter will be the time until a leak develops within that area, or the greater will be the total number of leaks after a given time. The pit depth-area relation depends on the irregularity of corrosion and differs for materials and soil conditions.

different

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From the foregoing considerations, it follows that if two materials are to be compared, they must be exposed not only to the same soil conditions, but they must also have the same exposed areas and be exposed for the same time. Otherwise adjustments which take account of these variables must be made. The difficulties involved in meeting these conditions greatly limit satisfactory comparisons of materials. Anyone desiring to compare materials should first determine whether his data meet the conditions for correct comparisons. If the conditions with respect to equal time of test and equal areas are met, the relative merits of the materials in soils may be different for other times and areas, especially if the times are short and the areas small.

On account of the effects of time and area on the data obtained from corrosion tests, it has been proposed (48) that corrosion in soils be expressed by an equation having three variables, the first representing the corrosion after some arbitrary period of exposure, the second expressing the effect of the period of exposure, and the third expressing the effect of area.

The use of such an equation would permit the comparison of materials or soils under any chosen conditions with respect to time and area of exposure. It would also permit the estimation of the number of leaks to be expected in any length of pipe after any period of service providing no part of the line had been renewed.

VII. THE MITIGATION OF UNDERGROUND CORROSION.

1. Selection of Exposure.

Under certain conditions some choice may be exercised in the location of structures underground. A soil survey may disclose local areas of corrosive soils which may be avoided. Well drained areas should be selected for the sites for graveyards, tank farms, filling stations and other projects requiring buried tanks or other containers. Rights of way for pipe lines may sometimes be modified to avoid swamps, alkali spots, peat bogs and other corrosive soils. Often other things are more important than the saving to be realized through any practical change in location, but the possibility of avoiding corrosion through an advantageous choice of soil conditions should be considered.

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Closely related to this is the drainage of low areas, drainage of the trench in which a pipe is to be placed, and the backfilling of the trench with sand or other non-corrosive material in places where the pipe passes through filled or contaminated ground.

The writer understands that several pipe line owners have experimented with the addition of lime or crushed limestone to pipe trenches, but no reports of the success of the experiments have reached him. Evans (9) reports success with backfills of lime.

Careful tamping of the soil around the lower half of the pipe will reduce voids and differential aeration. This practice is required in many cities for the protection of paving rather than to reduce corrosion. Pitting has been observed where rocks, sticks or other solid material have been placed in contact with pipe accidentally, and several pipe line companies take precautions to eliminate this cause of corrosion.

It has been observed that corrosion tends to increase with the depth at which pipes are laid. The added cost of deeper trenches usually takes care of this cause of additional corrosion.

2. Choice of Corrosion-Resistant Materials.

There is a long-standing and continuing demand for better pipe materials, and many materials are offered to meet this demand. That some materials are more resistant to corrosion than others can not be doubted. Whether the more resistant material is more economical is quite a different question, the answer to which depends largely on the cost of leaks.

There is little difference in the rates of corrosion of the commonly used ferrous pipe materials when they are exposed to the same soil conditions. These differences are of the same order of magnitude as the variations in the performance of different specimens of the same material. The average of the results of the Bureau of Standards (49) soil-corrosion tests indicate that wrought iron corroded slightly less and cast iron slightly more rapidly than Bessemer steel during the first twelve years of exposure, but that the relative merits of these materials differ for different soil conditions. The addition of a few percent of chromium to steel may slightly reduce the loss of weight but has little effect on the maximum pit depths (44, 50). The addition of nickel to steel seems to be slightly

more effective, but corrosion is not greatly reduced until the percentages of these materials become sufficient to materially affect the cost of the alloy. An iron alloy containing 14% of Si is very resistant to most soils though hard to machine and brittle.

According to Burns (51), lead is very resistant to conditions which are favorable to the production of films of lead sulfate or carbonate, but Shipley (52) found lead corroded by sodium carbonate. The Bureau of Standards tests show little corrosion of lead in soils containing carbonates and bicarbonates. Occasionally soils are encountered which cause the formation of deep isolated pits in lead pipe. In most soils corrosion penetrates lead a few thousandths of an inch, which is more than the thickness of most lead coatings applied to pipe. For this reason, as well as because they contain pinholes, lead coatings have not been generally successful underground.

Copper and alloys high in copper are very resistant to most soils except those which contain hydrogen sulfide, such as marshes. Brasses high in zinc are subject to dezincification in many soils. The corrosion of yellow brass is similar to the corrosion of cast iron in that the corrosion products largely remain where the corrosion occurs and thus preserve the form of the corroded material.

Zinc has been used or considered for use in the construction of burial vaults and caskets. It corrodes less rapidly and more uniformly than steel in many soils, and forms a partly protective coating in aerated soils. Its chief use underground is as a coating on steel and for cathodic protection. For the latter purpose it is essential that the zinc corrode, since the protective current is produced by galvanic action between zinc and steel.

3. Protective Coatings.

Almost if not quite as common as the demand for corrosion-resistant material is the demand for protective coatings. The popularity of protective coatings for pipes has been diminished in recent years by the realization that many of them were only partly effective and of but temporary value. Until the American Petroleum Institute (29, 53) undertook an extended investigation of bituminous coatings little was known of the effectiveness of these coatings or of the reasons for their failure to afford complete protection. An

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extended study of the reports referred to and of two others (54, 55) should be made by those interested in coatings. Briefly the results of the tests, which are summarized in table 8, showed that none of the 19 bituminous coatings tested completely prevented corrosion over a period of ten years. However, most of the coatings greatly reduced the corroded areas, the number of pits and the depth of the deepest pits. The coatings were therefore helpful over the period of the test. There is some evidence that after a coating has broken down corrosion may be accelerated, at least temporarily. This should be regarded as a possibility rather than as an established fact.

Many of the failures of the A.P.I. coatings were the result of faulty application; others are attributable to unwise choice of materials with respect to soil conditions. All of the coatings tested seemed to be subject to progressive deterioration due to pipe movement, soil stress, root growth, or penetration of moisture. It appears, however, that several of the thicker coatings would prevent serious pitting in most soils for much longer than ten years.

There is a general belief that coating materials and methods of application have been greatly improved since the A.P.I. tests were begun, but no one has undertaken to determine the extent of the improvement. A few reports on coatings recently installed indicate that some coatings still develop imperfections and that some companies have learned little regarding the conditions and precautions necessary for the production and application of an effective coating.

Within the last ten years considerable progress has been made in the development of rubber and synthetic resins as pipe coatings (56). Some of the most effective of these coatings require heat treatment for an hour or more. Vitreous enamels have also been tried in an experimental way and have yielded promising results, but local failures of some of the specimens of one enamel have been recorded.

Of the metallic coatings, zinc is the only one extensively used underground. Iron is protected through the corrosion of the zinc. It follows that the protection afforded by zinc can continue only while it remains to be corroded. The duration of protection will depend on the corrosiveness of the soil and the thickness of the coating. In the earlier Bureau of Standards tests a 3-ounce coating prevented pitting of iron pipe for ten years in all but one of a total of 47 soils. More recent tests (56) indicate that in some very corrosive soils a pipe with a 3-ounce coating of zinc may begin to pit in two years.

Table 3. Summary of conditions of line pipe under A.P.I. coatings after 10 years.

Symbol	Coating		Total feet in-pected	Unaffected percent	Rusted percent	Metal attack percent	Pitted percent	Depth deepest pit
	Thick-ness	Character						
	mils							mils
C	21	Outback coal tar	1. Gold Applications					
A	65	Asphalt emulsion	166	1.2	5.4	9.6	84.5	a322+
			178	0	0	1.7	98.3	a322+
N	60	Coal-tar-asphalt enamel	2. Enamels					
K	69	Coal-tar-asphalt enamel	152	13.8	13.8	10.7	62.0	264
M	58	Coal-tar enamel	183	7.2	8.2	29.6	55.0	195
L	80	Coal-tar enamel	151	0	0	2.0	98.0	231
			157	19.8	3.8	6.4	70.1	a322+
O	519	Asphalt mastic	3. Mastic					
			213	72.5	18.4	6.6	2.8	38
Y	29	Outback asphalt	4. Shielded Coatings					
F	419	Asphalt emulsion	164	1.2	10.4	18.3	70.0	200
G	63	Coal-tar-asphalt enamel	170	3.5	39.0	21.8	35.9	107
H	81	Coal-tar enamel	202	29.3	17.9	25.3	27.8	a322+
			177	43.0	4.0	5.1	48.0	240
			5. Reinforced Coatings					
B	107	Grease	208	0	4.3	29.4	66.3	89
S	150	Asphalt	166	0	1.7	23.5	75.3	290
E	151	Asphalt	192	4.7	8.9	36.5	50.0	197
Z	201	Asphalt	228	0.4	9.7	46.1	44.1	160
R	143	Asphalt enamel	208	20.2	9.2	20.2	50.5	197
U	171	Coal-tar-asphalt enamel	218	30.8	6.0	23.5	39.9	126
T	351	Coal-tar enamel	175	14.9	14.3	33.1	37.7	58
X	230	Asphalt	229	5.2	13.5	61.1	20.1	124
Total			3,537	14.7	10.0	22.9	52.2	

a Through pipe.

4. Cathodic Protection.

Since corrosion can only occur at points where the metal is anodic with respect to the adjacent electrolyte it might be prevented by making the entire pipe a cathode. This is accomplished by connecting the pipe to the negative pole of a source of direct current, the positive pole being connected to an electrode suitably placed in the electrolyte. This method of preventing corrosion is known as cathodic protection. Some of the more important of the many papers on this subject have recently been summarized in a paper prepared for distribution by the Bureau of Standards (57). This system of protection may be applied to coated or to unprotected pipe lines and to pipe networks already installed. Under some conditions, protection of pipes cathodically is less expensive than any other means of keeping them in service. The cost depends in part on the amount of current required, which is greatly reduced if the pipe is covered with an insulating coating. Even a poor coating considerably reduces the consumption of current. Whether coatings should be used in connection with cathodic protection is a much debated question, the answer to which depends on the cost, effectiveness, and life of the coating. Unfortunately, data on the life and effectiveness of coatings are quite limited and conflicting; but a fairly satisfactory answer regarding the advisability of combining cathodic protection and a protective coating can be obtained on the basis of reasonable assumptions as to all costs and as to the service to be expected of the coating.

5. Insulation and Insulating Joints.

Since an electrical current is an essential feature of most underground corrosion, anything which will interrupt this current will stop the corrosion. Most protective coatings are intended to do this. Their effectiveness has already been discussed. If corrosion is the result of stray currents, long-line currents or the joining of two different metals an insulating joint inserted where the current is greatest will prevent or retard corrosion. Since current in a pipe in an electrolyte may leave the pipe on one side of the joint and return on the other side, a long leakage path should be provided either by an insulating coating on either side of the joint, or by placing the joint in a manhole or box kept free from conducting material.

A number of inexpensive and effective insulating joints are on the market or may be improvised. Insertion of these joints in a new pipe line costs little, but installation in a working line is much more expensive and sometimes impractical. Insulating joints are especially useful in preventing contact between different metals which otherwise might cause galvanic action.

6. Non-Metallic Pipe.

Non-metallic pipe has been suggested for use in corrosive soils. Pipes made of bored logs were extensively used to carry water in the early history of this country and some of this pipe served many years. This led to the development of wood-stave pipe, which is now used quite extensively in certain parts of the country, especially where large diameter pipe is required. This type of pipe has proven satisfactory where it could be kept full of water or covered with moist non-corrosive soil. Corrosion of the iron bands used to hold the staves together has caused trouble in some localities.

About 1930 there was introduced into this country cement-asbestos pipe, which was developed in Italy in 1913, and had been used in several countries of Europe. The Underwriters' Laboratories, Inc. (58) has published a report on one brand of this pipe and has listed it for use with limitations. Cement-asbestos pipe absorbs some moisture from wet soils and does not have the strength per unit cross-section of steel or cast iron. As a pipe it performs mechanically more like cast iron than steel. It is apparently unaffected by alkali soils, but shows superficial softening when exposed to acid soils under some conditions.

VIII. SUMMARY.

There are a large number of sources of potentials which cause the corrosion of buried metal. The seriousness of corrosion underground depends largely on the character of the films or thicker deposits resulting from corrosion processes. Poor material is not an important cause of underground corrosion. The chemical composition of the soluble material in soils is an important factor in corrosion but when the soil contains only small percentages of soluble salts other factors control the rate of corrosion. Well drained soils are usually non-corrosive. Wet soils, organic soils, and soils high in soluble salts are usually corrosive. Stray currents cause corrosion only when they flow from metal to an electrolyte, usually the earth. Only direct currents cause corrosion under normal conditions.

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Much underground corrosion is attributable not to the character of the metal used or the soil but to conditions incidental to pipe-line construction, such as the inter-connection of old and new pipe, the crossing of different soils or soil horizons, voids in the backfill, and current picked up from other structures.

There are several tests which will indicate whether soils are potentially corrosive. When a sufficient number of tests are made they yield satisfactory indications as to the location and extent of corrosive areas. The correlation of the results of tests of single samples of soil with the corrosion observable at the points where the samples were taken may not be good because other factors than soil characteristics may control the corrosion, and because the soil samples may not be representative of conditions at the point of corrosion.

There is no standard or generally accepted criterion for corrosivity or corrosion resistance. The relative merits of materials with respect to corrosion may change with the time of exposure, the area exposed and the conditions of exposure.

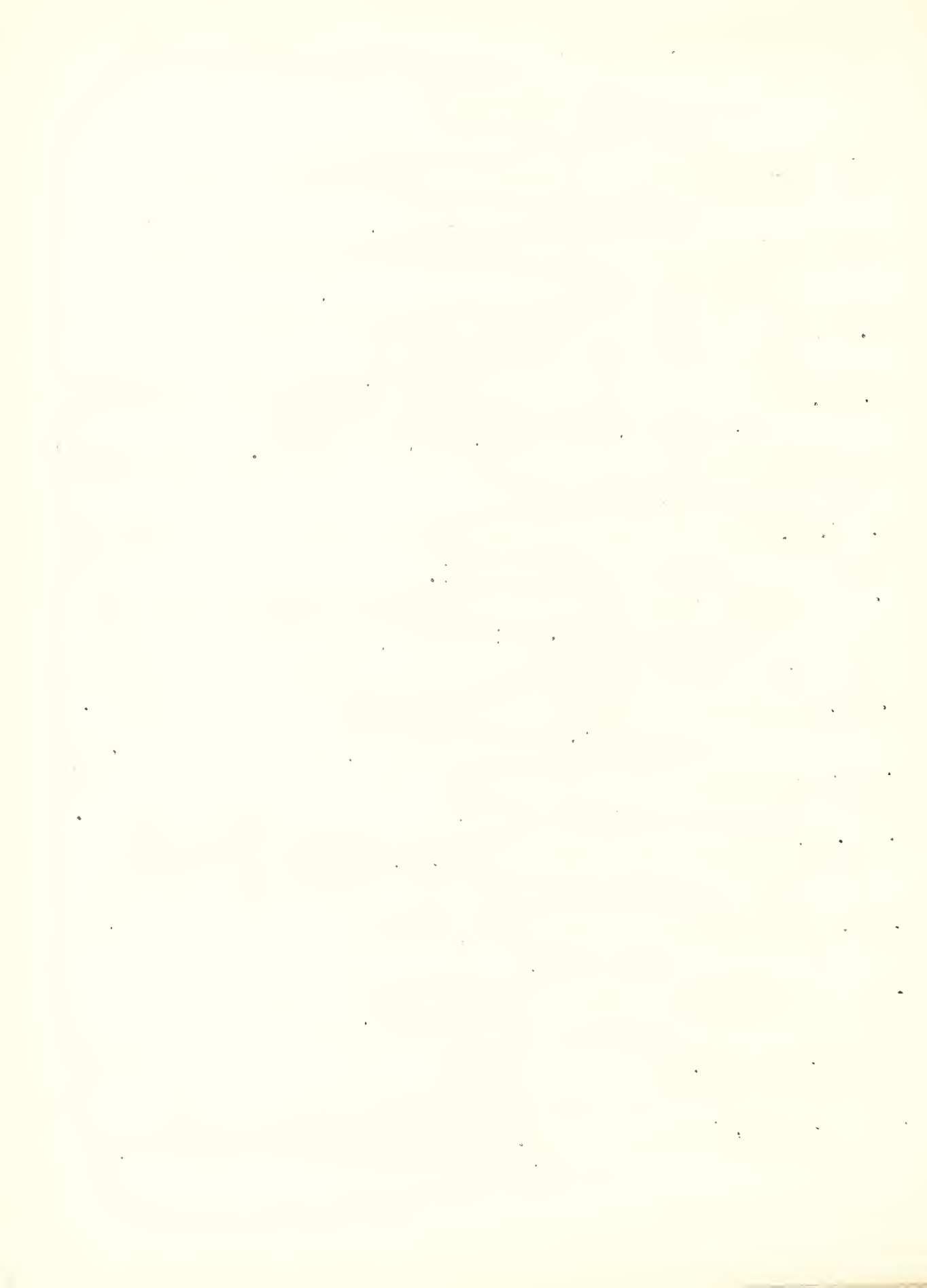
Usually most of the commonly used ferrous materials, including many low-alloy steels, corrode at nearly the same rates when exposed to the same soil conditions. Lead corrodes slowly in most soils because of the formation of protective layers of carbonate and sulfate. Copper and alloys high in copper corrode much more slowly than ferrous materials in most soils. Copper is much affected by soils containing hydrogen sulfide.

Bituminous coatings usually are imperfect or develop imperfections. Most of them after a few years permit some corrosion but the better coatings reduce losses of weight and pit depths for ten or more years. Zinc is the only metal extensively used for underground coatings. Its effectiveness is temporary.

Cathodic protection properly applied and maintained is an effective means of preventing corrosion. Under some conditions a combination of a protective coating and cathodic protection affords the most economical means of preventing corrosion.

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